IDENTIFICATION AND EVALUATION
OF MONITORING TECHNIQUES
FOR THE
PERFORMANCE OF A COMMUNICATION NETWORK

THESIS

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AFIT/GOR/ENS/95J-01

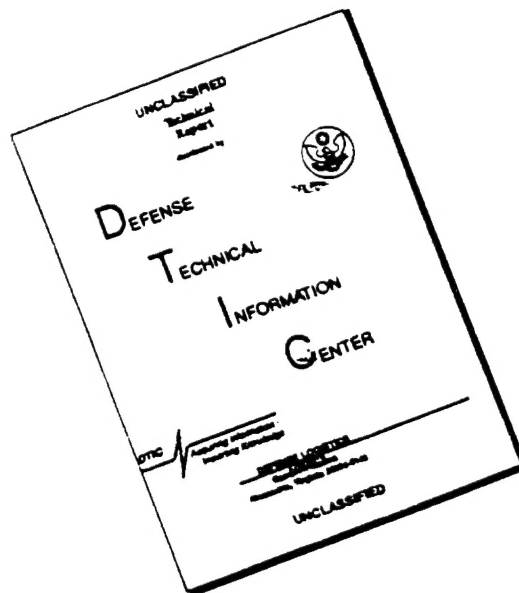19960327 008

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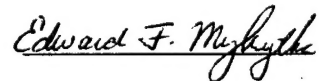Performance of a Communication Network

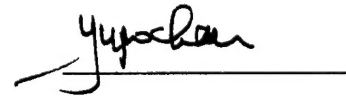DEFENSE DATE: 24 MAY 1995

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AFIT/GOR/ENS/95J-01

IDENTIFICATION AND EVALUATION OF MONITORING TECHNIQUES FOR
THE PERFORMANCE OF A COMMUNICATION NETWORK

THESIS

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PREFACE

The need is always present for monitoring the current performance of any existing communication network. In the presence of limited data on these networks, methods are needed to monitor a network over time in order to determine their performance and detect any degradation.

The purpose of this study is to identify viable performance measures for a communication network derived from limited data. Then, control chart procedures will be applied to these performance measures in order to monitor them over time. These control chart procedures should provide a straightforward and near-real-time technique for monitoring the performance of a communication network.

I thank my advisor, Dr. Edward Mykytka, for his excellent guidance through the world of statistical process control and for his "smiling" acceptance of my "unorthodox" timeline in completing this thesis. I also thank my reader, Dr. Yupo Chan, for his help in understanding communication networks and for his insights.

Finally, I thank my wonderful husband, Franco, for being "Mr. Mom" on quite a few occasions and for the enormous support he gave me. I also need to thank my newest "addition", Dominic, who completed this Master's degree right along with me and is probably an expert in control charts at the age of 5 months.

<div align="right">Maureen "Mo" Borgia</div>

Table of Contents

List of Figures

List of Tables

x

ABSTRACT

This study investigates the application of statistical process control methods to monitoring the performance of a communication network. The methods applied include four different types of control charts. The literature search uncovered only one previous study that used a control chart to monitor a communication network.

Using a case study of a communication network, four important issues for proper control chart usage are emphasized. These issues are: proper data collection rate due to autocorrelation, proper subgrouping of the data, ensuring that count data conforms to the assumptions of the binomial probability model before implementing p or np control charts, and viability of using subgroups of attribute data as measurement data on an x-bar chart. The results indicate that control charts are indeed a viable method for monitoring a communication network's performance over time, especially when the available data on the network is limited.

IDENTIFICATION AND EVALUATION OF MONITORING TECHNIQUES FOR THE PERFORMANCE OF A COMMUNICATION NETWORK

1. Introduction

1.1 Background

By definition, a communication network is represented by a set of nodes that are interconnected by transmission links. The nodes can be user terminals or switches that pass information along to the next node (7:3). The links can be wire, cable, radio, satellite links, or fiber optics (23:6). Links can be directed or undirected. On a directed link, communication can only take place in one direction between the nodes it connects whereas, on an undirected link, communication can take place in both directions (7:3).

The sponsor of this thesis is in charge of monitoring a communication network and evaluating its performance. The sponsor is seeking guidance on methods to:

> Proactively monitor the reliability, availability, and degradation of networks...; account for their performance under fully automated resource conditions through optimum resource utilization; and model new requirements and Level of Service Agreement specifications to validate the performance of the system (20:1).

Notional failure data was provided which represents the type of performance information that can be observed from the communication network. This data consists of a log of times that specific links changed state (from up to down or vice-versa). An example of this data is shown in . In addition, monthly summaries of overall network performance containing information, such as the average down time for any link and mean time between failure over all links, were provided.

Table 1.1 Example Log of Network Data

Date	Link Number	Failure Time	Up Time	FailureDuration
Mar 10	12	06:11:15	06:30:25	00:19:10
Mar 10	42	06:20:03	06:25:15	00:05:12
Mar 10	3	06:21:00	07:40:06	01:19:06
Mar 10	21	06:40:17	07:05:27	00:25:10
Mar 10	8	06:45:48	06:55:59	00:10:11

The performance of the communication network will be required to conform to Level of Service (LOS) Agreements that are to be developed between the sponsor and the customers of the communication network. However, no specified monitoring method or technique is currently in use, nor are LOS specifications and agreements currently defined. As stated above, the general categories of performance measures being considered for inclusion in these LOS Agreements are reliability, availability, and degradation. Appropriate measures of performance in these categories need to be identified and investigated for their merits towards representing the sponsor's communication network. These measures must be derived from the observable data of the network. Control charts were suggested by the sponsor as a possible technique for monitoring the network's performance and are the focus for this research.

1.2 Research Objectives

1.2.1 Overall

The primary objectives of this thesis are to (i) identify and evaluate possible statistical process control methods (primarily control charts) that could be used to proactively monitor communication network performance over time, (ii) automate the best of these methods into a user friendly software package, and (iii) relate .these methods to the development of appropriate LOS Agreements.

1.2.2 Specific Requirements.

The following specific requirements must be accomplished in order to complete this research:

1. Identify and evaluate related work in this field.
2. Identify possible performance measures that can be observed and used to represent the reliability, availability, and degradation of the communication network over time.
3. Identify appropriate statistical process control techniques that can be used to monitor each candidate performance measure.
4. Develop an appropriate model that could be used to describe the theoretically expected performance of the network to be used in developing appropriate 'standards' for control charts LOS Agreement specifications.
5. Identify methods for relating the proposed model and process control techniques to potential LOS Agreements.
6. Evaluate the proposed control techniques through:

   - consideration of theoretical properties based on a model of network operation and performance,

- validation and demonstration of these procedures through a case study of network performance, especially demonstrating how degradation can be monitored, and

- since data from the actual network is not available, development of a model of network operation from which simulated data can be observed.

7. Develop EXCEL spreadsheets and macros for implementing the proposed control techniques (8).

1.3 Assumptions

Based on discussions with the sponsor and concurrence with other research in this area, the following assumptions are used throughout this research effort unless otherwise noted:

1. Nodes are not subject to failure. [The precedence for this assumption was set in a previous thesis effort for the sponsor by Van Hove (27:10, 54-5). Networks with failing nodes can be modified to conform to this assumption by replacing the failing node with two reliable nodes connected by a failing link as demonstrated in previous theses by Yim (30:10,49), Gaught (9:17,22), Jansen (12:40) and Van Hove (27:55).]

2. Links are subject to total failure only, i.e., they are either 'up' or 'down' and they do not operate in a degraded condition. Further, a link's failure can be due to any cause including routine maintenance. [Total failure of links is a common assumption used in previous thesis efforts by Yim (30:3), Gaught (9:3), Jansen (12:3), and Van Hove (27:5).]

3. Link failures are independent. [This assumption is consistent with previous thesis efforts by Yim (30:17,51), Gaught (9:3), Jansen (12:3), and Van Hove (27:10).]

4. Links are directed (one-way); flow is permitted in one direction only. [This assumption is also consistent with previous thesis efforts by Yim (30:3), Gaught (9:3), Jansen (12:3), and Van Hove (27:40,47). This assumption only impacts the computation of the number of paths existing between a source and sink node. This number is then used in computing certain network performance measures. This assumption can be relaxed, but then specific information about network structure and protocols implemented is required.]

5. Only the 'status history' of links can be observed from the network, i.e., a log of times for link status changes (up or down). No other network information is available such as 'flows' (amounts of information transmitted over links per time interval), 'error rates' (proportions of transmitted information that is correctly received), or link reliabilities. This assumption is consistent with the notional data and monthly summaries provided by the sponsor.

5. Changes in link status are observed and recorded in real time but are reported to a 'network monitor' only at 300-second intervals. The 'network monitor' is that entity which is monitoring the network. [This assumption is consistent with the information and notional data provided by the sponsor.]

6. The network is assumed to perform under fully automated resource conditions which enable it to optimally use its resources. Thus, for example, if a link fails, traffic which could use that link is automatically rerouted to an alternate path (if available).

7. No Level of Service (LOS) Agreements currently exist.

1.4 Scope

Currently, the sponsor monitors the network in terms of which links are "up" and "down", and records this information in a log of the times of their failure and repair. This thesis will be limited to an examination of statistical process control (SPC) procedures that can be applied to performance measures which can be computed from this available data. Additionally, the performance of a communication network can be monitored from three viewpoints. First, the network as a whole can be monitored by aggregating measurements and readings over all links in the network. Second, the network can be monitored from a customer's perspective by monitoring the paths between the customer's source-termination (s-t) nodes. Finally, each link in the network can be individually monitored for indications of degradation or failure.

2. Literature Review and Assessment

This chapter presents a review of literature applicable to the use of statistical process control techniques for monitoring communication network performance. In addition, the performance measures applicable to the sponsor's communication network and the observable data are identified. The literature reviewed covers books, current journals, conference proceedings, and theses. Following sections will discuss commonly used performance measures, performance measures applicable to the sponsor's network, prior theses in communication network performance, statistical process control (SPC) techniques, and prior applications of SPC techniques to communication networks.

2.1 Common Performance Measures

There are certain measures of communication network performance that are commonly used in the literature. These are: time delay, reliability, availability, and bit error rate. Each is discussed below.

2.1.1 Time Delay.

A number of sources identify time delay as an important measure of performance. Each source uses different names for this delay, such as end-to-end time delay (23:22), average time in system for all messages (7:91), network average delay (15:1108), and message delay (14:24) but they all have the same meaning. Unfortunately, this measure is not available in the data that is currently observed from the network and, hence, time delay will not be used as a performance measure in this thesis. (If time delay could be

observed, it could be readily monitored using the variables control charts discussed in subsequent sections.)

2.1.2 Reliability.

Another common and useful measure of communication network performance is reliability (12:7). Reliability is defined as the probability that a system/component will operate without degradation and be able to perform a certain mission for a certain length of time given that the system/component was operating initially (19:43).

The reliability of a specific link can be computed theoretically if the time to failure distribution for that link is known. In particular, if the time to failure for a link can be modeled as a random variable that has probability density function (PDF) f(x), then the reliability of that link can be computed as (21:433-4):

$$p(T) \equiv P[\textit{link still operating at time } T] = \int_0^T f(s)ds$$

Then, the reliability associated with a particular path composed of n independent links arbitrarily numbered 1 through n is given by:

$$r(t) = \prod_{i=1}^{n} p_i(t)$$

where $p_i(T)$ denotes the reliability of the ith link. If we could then represent the portion of the network connecting a source node, s, to a termination node, t, as a collection of k independent and parallel paths, then the reliability of that portion of the network could be determined as:

$$R(T) = 1 - \prod_{j=1}^{n} \left[1 - r_j(T) \right]$$

where $r_j(t)$ represents the reliability of the jth path.

Unfortunately, this last expression is not generally appropriate for most communication networks since, even though individual links may behave independently of one another, alternate paths may share common links and, thus, would not be not independent. In such situations, the reliability of a particular portion of the network can be determined by first developing an appropriate structure function as described, for example, in (21:412-17). This development is omitted here since the approach (i) is straightforward but tedious, (ii) would need to be applied uniquely to each source node-termination node pair, (iii) requires link time-to-failure distributions to be known, and (iv) provides a means of evaluating the *expected* performance of the system but has limited value for *monitoring* system performance over time. It is important to note, however, that such a system reliability approach would appear to provide a useful and tractable way to model communication between particular pairs of source and termination nodes.

The formal definition of reliability, however, does suggest some related performance measures. Although these do not directly measure reliability per se, they do provide meaningful measures that can be used to detect changes in the reliability of the network or its components (i.e., of links, paths, or collections of paths). One such measure is the proportion of components that do not fail over a specified time interval. Another is the Mean Time To Failure (MTTF), defined as the expected length of time a component successfully operates before it fails. For a specific link, this is simply the mean of the time-to-failure distribution. A closely related measure is the Mean Time Between Failures (MTBF), which is the Mean Time To Failure plus the mean time to repair (MTTR). Strictly speaking, however, since MTBF explicitly considers the possibility of repair, it perhaps should be classified among the measures of availability which follow.

2.1.3 Availability.

Availability is defined as either the probability that a system is functional at a given time or the proportion of time that a system is functional (25:41). This is different from the definition of reliability in that reliability is the probability that a system will operate without degradation for a certain *length of time* instead of *at a given time*. It implicitly recognizes that components are repaired once they fail. Myers and others list three more specific definitions of availability:

1. *Instantaneous availability*. The probability that the system will be available [functional] at any random time t.
2. *Mission availability*. The proportion of time in an interval that the system is available for use.
3. *Steady-state availability*. The proportion of time that the system is available for use when the time interval considered is very large. (19:49)

One common equation for computing steady-state availability is (19:52):

$$A = \frac{MTTF}{MTTF + MTTR}$$

where $MTTF$ = Mean-Time-To-Failure and $MTTR$ = Mean-Time-To-Repair. Kubat gives a definition of network availability that agrees with mission availability as defined above (13:309):

$$A = \frac{E\{network\_uptime\_during\_one\_cycle}{E\{cycle\_time\}}$$

where a *cycle* is the time interval of interest.

2-4

2.1.4 Bit Error Rate.

One final measure of performance that is indicated in the literature as being important is the bit error rate (BER). This is a measure of how many bits of a message are received in error divided by the total number of bits received (4:Ch 1, 2). BER provides a common measure of network degradation but, since this data is not currently observable from the sponsor's communication network, this measure will not be used in this research effort.

2.2 Applicable Performance Measures

In the preceding section, a number of commonly-used communication network performance measures were introduced. Most of these are measures of theoretical or expected system performance which require knowledge of certain system characteristics, such as time-to-failure distributions for each link. Although these measures provide a useful means of describing a system, they are not directly useful for monitoring *current* network performance. Instead, measures that can be computed based on the observed performance of the network are required. This section describes the particular measures, or quality characteristics of the communication network, that will be used in this research to evaluate network performance.

As was stated in Chapter 1, the communication network can be monitored from three different viewpoints: overall network performance (aggregating measurements over all links at a system level), network performance for a given customer's (s-t) pair (at an s-t level), and individual link performance (at a link level). Each of these viewpoints has performance measure(s) that are best suited to them. Remembering the sponsor's initial goal to monitor the **reliability**, **availability**, and **degradation** of networks, some appropriate performance measures are now identified to accomplish this goal.

Since no information is available about the processes by which links degrade over time, nor can this be *directly* measured from the data available, **degradation** will be monitored *indirectly* through observation of performance measures related to **reliability** and **availability**. These measures can, in turn, be expected to reflect any degraded performance of the network. To facilitate this indirect monitoring of degradation, it is assumed that links either fail more often or remain down for longer periods of time when they are in a degraded state.

2.2.1 Overall Network Performance.

Since the link failures are assumed to be independent, one measure of overall link reliability, termed **p-up** in this study, is the proportion of operating links that are observed at a given instant of time (specifically at the 300 second reporting interval described in Chapter 1):

$$p - up = \frac{total\_operating\_links}{total\_\#\_links}$$

As network performance degrades, this measure would be expected to show a decrease since fewer links would be operating. An 'opposite' measure/proportion, which will be termed **p-down**, can also be calculated at any instant of time as:

$$p - down = \frac{total\_down\_links}{total\_\#\_links}$$

This measure is expected to increase as network performance degrades since more links will be down. Alternately, the number of links up or links down at any instant of time could also be used as a performance measure. Links down, termed **DwnLnk**, will be used arbitrarily in this study. This measure is expected to increase with network degradation.

An important point here is that at any reporting time, all that needs to be checked for the performance measures to be computed is the status of each link (up or down). Failure and repair times are not used in the above measures and thus, they provide a 'snapshot' of the network status at each reporting time.

2.2.2 Network Performance for a Customer.

A measure is needed to express network performance for a given customer's source-termination (s-t) node pair. This measure/proportion, which will be denoted as **p-path**, can be calculated every reporting time as:

$$p - path = \frac{\#\_operating\_paths(s-t)}{\#\_total\_paths(s-t)}$$

This proportion does not directly measure path reliability since the paths are not all independent, but it is a useful indicator of (s-t) network performance nonetheless. As network performance degrades, this measure would be expected to show a decrease since fewer links would be operating which, in turn, should cause fewer paths to be operating. Here too, at every reporting time all that needs to be checked is the status of each link which, in turn, is used to determine the status of each path. Failure and repair times are not used, just a 'snapshot' of the network at each reporting time.

The communication network monitored by the sponsor is, generally, a collection of 40 to 50 nodes, each connected to between 1 and 10 links. As such, the network is expected to offer at least a moderate number of alternate paths between most (s-t) node pairs. In this case, any degradation in link performance may have only a slight to moderate impact on overall network or customer (s-t) performance. This small impact may be difficult to detect using the previous described 'larger-scale' network

performance measures. As a result, a proactive monitoring strategy would appear to place emphasis on monitoring individual link performance in order to detect and correct 'low-level' degradations before they significantly impact overall network performance. For this reason, the bulk of attention in this thesis is focused at the individual link level. This is fortuitous because performance at this level is also the easiest and most straightforward to monitor.

2.2.3 Individual Link Performance.

This goal requires data to be collected for each link individually. A common **Availability** measure can be calculated for each link as:

$$Availability = \frac{total\_link\_uptime\_during\_one\_time\_interval}{total\_interval\_time}$$

for intervals of 1 hour and/or 1 day. Care must be taken in choosing the cycle length, since a cycle length shorter than the mean time between link failures would not produce an accurate calculation due to lack of enough (or any) representative data during the interval. This will be demonstrated explicitly during the case study. Any degradation of an individual link's performance can be expected to decrease this availability measure. A related measure or proportion, denoted **p-link**, can also be calculated by computing the proportion of reporting times during an interval that the link is found to be operating:

$$p-link = \frac{total\_times\_link\_is\_found\_operating\_per\_interval}{total\_reports\_per\_interval}$$

for intervals of 1 hour (12 reports per hour) and/or 1 day (288 reports per day). Again, any degradation of an individual link's performance is expected to decrease this performance measure.

For each link, the **Time Between Failures (TBF), Time to Failure (TTF)**, and **Time to Repair (TTR)** can be calculated for each failure from the log of failure and repair times. Also, each link's cumulative **Mean Time Between Failures (MTBF), Mean Time to Failure (MTTF)**, and **Mean Time to Repair (MTTR)** can be calculated over all past failures after each failure/repair occurs. For these measures, a degradation of an individual link's performance is expected to decrease TBF, TTF, MTBF and MTTF and/or increase TTR and MTTR. Also, from the above measures, another availability measure, call it **SSA**, can be calculated for each link individually after each repair as:

$$SSA = \frac{MTTF}{MTTF + MTTR}$$

This is a steady-state availability measure and will be more accurate as time goes on (the MTTF and MTTR measures are cumulative). Since this is a steady-state measure, as time goes on it is expected that changes will become harder and harder to detect. This expectation will be investigated in the case study. In this last category of performance measures just described, the actual failure and repair times are used in addition to the 'snapshot'.

2.2.4 Summary of Performance Measures.

Quite a few performance measures have been identified as candidates for representing the performance of a communication network. These performance measures were chosen on the assumption that the only data available from the communication network is link failure times, repair times, and status (up or down) at a given time. These identified measures are investigated in subsequent chapters.

2.3 Previous Theses on Communication Network Performance

Previous theses are investigated in order discover any applicable methodologies or insights that will aid and support the current research effort. There are five previous theses on communication network performance that were accomplished for the sponsor. These were accomplished by Yim (30), Bailey (2), Gaught (9), Jansen (12), and Van Hove (27). Yim modeled the expected maximum flow of a network to determine optimum investment strategies that will improve stochastic communication network performance via arc capacity (30:2,25,92). An arcs is another term for a link (7:3). Bailey used Monte Carlo simulation to find the expected throughput and expected reliability of a stochastic communication network (2:1). Gaught built on Yim's work and developed further investment strategies for improving stochastic communication network performance via arc capacity and an additional measure, arc reliability (9:2,21). Jansen investigated the tradeoffs between maximizing throughput and maximizing reliability of a stochastic communication network (12:2-3). Most recently, Van Hove developed stochastic network flow models of a communication network in order to determine bounds on average delay, bit error rate, throughput, and reliability depending on the utilization level of the network (27:xi).

Although these theses efforts provide means of modeling the performance of a network over time, they tend to be focused on the *flow of information* through the network. As such, they require information that is not assumed to be known or observable in this thesis and, thus, appear to provide little relevant basis for this research.

In addition, these models tend to represent the behavior of links in the network in a somewhat different fashion from that assumed or observed in this research. For example, Van Hove defines the reliability of a link as "the proportion of time a component ... is expected to be functional" which, as seen previously, is also a measure of availability (27:10-11). He models this by assuming that, within a specified interval of

time, a link will either be up or down with a fixed probability, p, that it will be up. He implicitly assumes that changes in state occur at the start of these time intervals and explicitly assumes that a link's status during a given time interval is independent of its status in any other time interval. Although Van Hove does not advocate any particular duration for this time interval, it appears to be small; a one second interval is used within a case study.

Although this structure will produce a modeled link that is up the correct proportion of time, the number of state changes it undergoes or, equivalently, the durations of its up and down times, may not correspond to those in the actual system. One way to see this is to recall that the availability, p, for a given link can be determined from information about its MTTF and MTTR via:

$$p = (MTTF) / (MTTF + MTTR)$$

Clearly there are an infinite number of possibilities for MTTF and MTTR that could produce the same value of p. Hence, Van Hove's model does not account for the particular up and down time dynamics of the link. (This behavior, perhaps, could be modeled by relaxing the assumption of independent time intervals and explicitly recognizing that the probability that a link will be up in a given time interval depends on its state in the preceding interval.)

2.4 Statistical Process Control (SPC) Techniques

Statistical process control techniques, especially control charts, are the primary techniques under investigation in this thesis to monitor and evaluate the performance of the sponsor's communication network. Numerous sources discuss the various

techniques, or methods, of SPC. Two prominent, and pretty much all-encompassing, books on these methods are by Montgomery (18) and Ryan (22). These two sources overlap quite a bit, hence I will mainly cite from one of them and use the other to cover any gaps. Montgomery defines SPC as, "a powerful collection of problem-solving tools useful in achieving process stability and improving capability through the reduction of variability," and lists seven major tools of SPC (18:101):

1. Histogram

2. Check sheet

3. Pareto chart

4. Cause and effect diagram

5. Defect concentration diagram

6. Scatter diagram

7. Control chart

Each of these tools will be described below, and their relevance to this research will be established.

2.4.1 Histogram.

A histogram is a graph used for looking at the raw data collected from a process. The observed frequencies are plotted against the observed values and facilitates the display of three properties of the data:

1. Shape

2. Location, or central tendency

3. Scatter, or spread

These properties provide insight into the process from just the raw data (18:24). Since the sponsor wants techniques to *monitor* the network over *time*, this procedure is not appropriate and will not be used.

2.4.2 Check Sheet.

A check sheet is useful in collecting historical or current operating data about the process. It summarizes the data that is collected (types of defects for example) by categorizing and totaling the data. A time-oriented summary is useful in identifying trends or other important patterns in the data collected (18:118). This type of data (types of failures, etc.) is not available, hence this procedure will not be used.

2.4.3 Pareto Chart.

A Pareto chart is "simply a frequency distribution (or histogram) of attribute data arranged by category"(18:120). Just as in the histogram discussed earlier, the frequency of each observed attribute (like values in the histogram) are plotted against the observed attribute types. The difference here is that the observed attributes are not numerical values as in the histogram. They are qualitative instead of quantitative. This procedure, like the histogram, does not monitor the data with respect to time, hence, it will also not be used.

2.4.4 Cause and Effect Diagram.

Once a defect has been identified in a process the cause and effect diagram is used as a trouble-shooting aid to find possible causes of the defect . It is simply a pictorial diagram showing categories of causes and enumerated possible causes contained in each category (18:121-4). Once again, this type of data (causes for failures) is not available so this procedure will not be used.

2.4.5 Defect Concentration Diagram.

This diagram is a pictorial representation of the actual unit that is produced by the process. The defects are drawn on the unit in order to determine if physical location of the defect can provide insight into the cause of the defect (18:124). This pictorial procedure is not applicable since simply showing link failures on a diagram does not provide much insight as to the cause of the failures.

2.4.6 Scatter Diagram.

The scatter diagram is used to identify *potential* relationships between two different variables in the process. Data must be collected on the two variables and then plotted against each other. The resulting plot is then evaluated for any indicated patterns (i.e. slope, curvature, etc.) (18:125). This procedure is potentially useful if there is reason to believe that two of the performance measures are correlated. However, this procedure is only used to identify *potential* relationships, not to indicate a cause. The depicted relationship could be caused by another measure of something completely different (18:126).

2.4.7 Control Chart.

A control chart is a graphical display of some measured characteristic of a process that is plotted over time. The center line on the chart is the average value of the characteristic. The two other lines on the chart, one above and one below the center line, are the upper and lower control limits (UCL and LCL respectively). These limits are chosen such that nearly all of the characteristic points will fall between them when the process is "in control." When a point plots outside these limits, this is evidence that the process is "out-of-control" and an investigation is required to find the cause of this behavior in the process. This cause is called an assignable cause (18:103).

2-14

Assignable causes are sources of process variability that are other than the chance causes (background noise) inherent in the process (18:102). A sample control chart is shown in Figure 2.1.
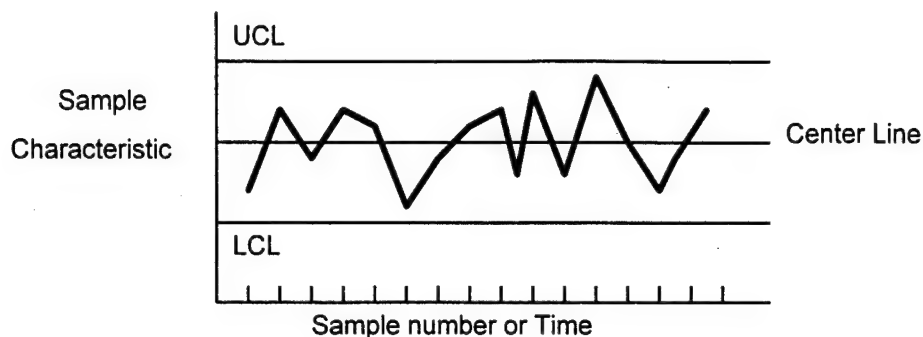
Figure 2.1 Sample control chart

There are numerous types of control charts that are used to display different types of characteristics. The two main categories of these types of control charts are: Control Charts for Attributes and Control Charts for Variables. These different types of charts are described next.

2.4.8 Control Charts for Attributes. Attributes are characteristics of a process that cannot be conveniently represented numerically. An example of this type of characteristic is the status of a link being 'up' or 'down'. Three widely used attributes control charts are the p chart, c chart, and u chart (18:147).

2.4.8.1 P chart. This is also called a control chart for fraction nonconforming . The population fraction nonconforming is the ratio of the number of nonconforming items in a population to the total number of items in a population (18:148). This ratio is computed for each sample using the total number of items in a sample. This chart would depict the fraction of components that are down (nonconforming) in the network. A variation of this chart also exists for the fraction

conforming, also called a p chart, and for the number of nonconforming items, called an np chart (18:148,162).

2.4.8.2 C chart. This is also called a control chart for nonconformities. This chart depicts the number of nonconformities observed in a unit. The unit is a sample of constant size (usually one but not always) (18:172).

2.4.8.3 U chart. This is also called a control chart for nonconformities per unit. This chart depicts the average number of nonconformities per unit and is used when the unit sample size is not constant (18:176-80).

2.4.9 Control Charts for Variables. When the quality characteristics of a process can be expressed as a numerical measurement, control charts for variables can be used. The characteristic that is measured is called a variable. It is standard practice in using these charts to plot both the process mean and variability on separate charts. This can be accomplished using x-bar charts, R charts and S charts (18:201).

2.4.9.1 X-bar chart. This is also called a control chart for means. This chart depicts the mean (average value) of the measured characteristic in a sample of observations from the process (18:203).

2.4.9.2 R chart. This is also called a control chart for the range. This chart depicts the range of values (the difference between the largest and smallest observations) of the measured characteristic in a sample from the process. This chart is used to monitor process variation (18:203-5).

2.4.9.3 S chart. This is also called a control chart for the standard deviation. This chart depicts the sample standard deviation of the measured characteristic in a sample from the process. This chart is also used to monitor process variation and is preferred over the R chart when either the sample size is moderately large (greater than

10 or 12) or the sample size is variable (18:230). A variation of this chart also exists for sample variance (S^2), called an $\underline{S^2\ chart}$ (18:239).

2.4.10 Runs Rules. A disadvantage of all of the previously discussed control charts (also known as Shewhart control charts) is that they ignore any information given by the entire sequence of points on the chart. They only evaluate the last plotted point on the chart. (18:279) This can be "remedied" by applying the following "sensitizing rules" (or runs rules) to a control chart to detect an "out-of-control" condition:

1. One or more points outside the control limits.
2. A run of at least eight points, where the run could either be a run up or down, a run above or below the center line, or a run above or below the median.
3. Two of three consecutive points outside the 2-sigma warning limits but still inside the control limits.
4. Four of five consecutive points beyond the 1-sigma limits.
5. An unusual or nonrandom pattern in the data.
6. One or more points near a warning or control limit. (18:117,279)

These runs rules are applied to control charts to better detect a small shift in the process (on the order of about 1.5σ or less). Hence, they should definitely be applied if the process were expected to 'decay' or 'wear down' slowly over time. But if these extra rules and warning limits are seen as too cumbersome, two other control charts can be used, CUSUM and EWMA charts .

2.4.11 CUSUM Charts. The CUSUM chart is a cumulative-sum control chart. This type of chart can be used for many different sample statistics such as averages, ranges, standard deviations, and fractions nonconforming, and is particularly effective

2-17

with samples of size one (18:280,299). This chart is effective in detecting small process shifts because it incorporates information from several samples instead of just one like the x-bar chart. This is accomplished by plotting the cumulative-sums of the deviations of the sample values from a target value. For example, if x-bar$_j$ is the average of the *j*th sample and μ_0 is the target value for the process mean, the cumulative-sum is calculated by:

$$S_i = \sum_{j=1}^{i}\left(\bar{x}_j - \mu_0\right)$$

where S_i is the cumulative-sum up to and including sample i (18:279-80). If the process remains in control at the target value μ_0, S_i should fluctuate around zero. Hence, an upward or downward trend indicated on the chart is evidence that the process has shifted. To determine whether the process is out-of-control, a V-mask procedure is applied to the CUSUM chart. The V-mask procedure is similar to control limits on the previous Shewhart control charts. Detailed procedures for constructing and using the CUSUM chart and the V-mask along with a tabular form of the CUSUM are contained in Montgomery (18:282-296) and Ryan (22).

2.4.12 EWMA Charts. The EWMA chart is an Exponentially Weighted Moving-Average control chart, also called a Geometric Moving Average chart. This chart is also effective in detecting small process shifts, can also be extended for other sample statistics besides sample averages, and is also effective with samples of size one (18:299-300,306) (22:122). The EWMA is a weighted average of all previous sample statistics. Hence, it incorporates information from several samples instead of just one like the x-bar chart. An out-of-control condition is determined from control limits similarly to

Shewhart control charts. An advantage of the EWMA over the CUSUM is the EWMA's ability to provide a forecast of where the process statistic will be at the next time period. One downfall, though, of both the EWMA and the CUSUM charts is that they do not react as quickly to large shifts in the process as the x-bar chart does. Therefore, to cover both large and small shifts in a process, Montgomery suggests using both x-bar and EWMA procedures together as either separate charts or even on the same chart with each one's respective limits plotted, or using both x-bar and CUSUM procedures together on separate charts. (18:297,306) Detailed procedures for constructing and using the EWMA chart are contained in Montgomery. (18:300-6)

2.5 Prior Applications

Only two instances of an attempt to apply SPC techniques to the communication network field were found. The first applies control charts not to a communication network, but to the monitoring of software development for GTE Communications Systems Corporation (29:29.4.1). The second more relevant source is a Master's thesis by Beadles from the Naval Post Graduate School which gives an overview of "basic SPC tools that are common to most total quality organizations [and] ... highlights more sophisticated tools used in the communications industry" (3:2). Also presented in this thesis is a case study of applying SPC method for improving a communications process. Although Beadles' thesis provides a comprehensive survey of SPC tools and other statistical methods for process improvement, little attention is given to monitoring a network over time (with the exception of a case study in which control charts are used to monitor the average time to clear an AUTOVON circuit) (3:86-94). Thus, Beadles' thesis provides a useful review of SPC and statistical techniques for communications engineers but provides little particular relevance to the objectives of the current thesis.

2-19

2.6 Summary

Knowing the observable data from the sponsor's communication network, the applicable performance measures have been identified. Of the many SPC techniques available, control charts seem well suited to monitoring these identified performance measures. The literature reviewed to date has not applied this SPC technique to monitoring these particular performance measures of a communications network. Hence, the applicability of control charts to monitoring these performance measures will be investigated in this research.

3. Methodology

Now that applicable performance measures have been identified, methods for using control charts to monitor these measures are discussed in detail below. Also, as stated in Chapter 1, data from the actual communication network as well as the description of the network's topology was not available from the sponsor. Therefore, in order to obtain sample data for charting purposes, a computer simulation model was created to generate data that is expected to be representative of that generated by the actual communication network. This simulation model is also discussed below.

3.1 Control Charts

There are many different types of control charts available for use. This section describes the usage of what appear to be the most applicable types for the performance measures identified in the previous chapter. These types are: x-bar and R charts, XmR charts, and p charts. Each is discussed below.

3.1.1 X-bar and R Charts.

These charts are used for data that are numerical measurements of the system being monitored(18:201). These measurements are then organized into subgroups (samples) of size greater than one and each sample is summarized by an average (x-bar) and a range (R) (28:40). The sample x-bars are plotted against time on the x-bar chart which to monitor the process mean, while the sample ranges are plotted on the R chart which to monitor the process variability or dispersion (18:201). If the mean (μ) and standard deviation (σ) of the distribution of the measurements taken on the process when

it is in-control are known, the upper and lower control limits (UCL and LCL respectively) and the centerline (CL) for the x-bar chart are calculated as:

$$CL = \mu + 3\frac{\sigma}{\sqrt{n}}$$
$$CL = \mu$$
$$LCL = \mu - 3\frac{\sigma}{\sqrt{n}}$$

and the limits for the R chart are calculated as:

$$CL = D_2\sigma$$
$$CL = d_2\sigma$$
$$LCL = D_1\sigma$$

where
$$D_1 = d_2 - 3d_3$$
$$D_2 = d_2 + 3d_3$$

are tabulated constants dependent on sample size given in Appendix A (18:221).

If the in-control process mean and standard deviation are not known, they must be estimated from the sample data. This sample data is typically taken from the process when it is assumed to be in control and then the mean is estimated as the grand average of m sample averages based on the measurements:

$$\bar{\bar{x}} = \frac{\bar{x}_1 + \bar{x}_2 + \cdots + \bar{x}_m}{m}$$

where m = number of samples.

The standard deviation is estimated from the ranges of the m samples via:

$$R_m = x_{max} - x_{min}$$

$$\bar{R} = \frac{R_1 + R_2 + \cdots + R_m}{m}$$

$$\hat{\sigma} = \frac{\bar{R}}{d_2}$$

where d_2 is a tabulated constant for various sample sizes also given in Appendix A. In this case, the control limits for the x-bar chart are now calculated as:

$$CL = \bar{\bar{x}} + A_2 \bar{R}$$

$$CL = \bar{\bar{x}}$$

$$LCL = \bar{\bar{x}} - A_2 \bar{R}$$

where

$$A_2 = \frac{3}{d_2 \sqrt{n}}$$

is another tabulated constant given in Appendix A (18:203-5). The control limits for the R chart are calculated as:

$$CL = \bar{R} + 3d_3 \frac{\bar{R}}{d_2}$$

$$CL = \bar{R}$$

$$LCL = \bar{R} - 3d_3 \frac{\bar{R}}{d_2}$$

where

$$\hat{\sigma}_R = d_3 \frac{\bar{R}}{d_2}$$

3-3

These limits can be redefined as:

$$CL = \overline{R}D_4$$
$$CL = \overline{R}$$
$$LCL = \overline{R}D_3$$

where

$$D_3 = 1 - 3\frac{d_3}{d_2}$$

$$D_4 = 1 + 3\frac{d_3}{d_2}$$

are more tabulated constants given in Appendix A (18:205-6).

3.1.1.1 Rational Subgroups. When monitoring a process, an analyst often has some flexibility in determining when measurements should be taken from the process and how these measurements should be grouped over time into samples for plotting. Ideally, these measurements should be taken so as to minimize the variation (range) within the samples and maximize the variability between samples . This is necessary since the control chart limits are calculated using this *within sample* variation and if it is too large, the control limits will be too wide and are not able to detect variation *between* the samples (28:100). In general, the subgroups should be selected to maximize the chance of an assignable cause occurring between samples and minimize the chance of it occurring within a sample. This concept is called rational subgrouping (18:113).

There are two approaches for selecting rational subgroups. The first approach is used if shifts in the process are of interest. Here, each sample (subgroup) should contain measurements that are observed as close together as possible. This should ensure that the samples are independent of each other and minimizes the chance of variability within the sample since the units are close together. If an assignable cause occurs, it is more likely to happen between samples than within a sample (18:113).

3-4

The second approach is used when the sample is to be representative of process performance since the last sample. Subgroups chosen this way are usually spread out over the entire sampling interval. When data is collected in this way, care must be taken in estimating the within sample variability since an assignable cause could occur during the sampling interval. A shift in the process mean may then cause the range within a sample to be very large. This could cause estimated control limits to be too large, or it could cause points on the R chart to plot out-of-control (indicating a shift in the process variability) when the shift has been in the process mean. This must be watched when interpreting control charts with these types of subgroups (18:113-4).

3.1.1.2 Autocorrelation Between Samples. The standard application of control charts and runs rules assumes that, when a process is in control, samples taken from that process are independent. This may be a factor in the sponsor's communication network where the basic reporting interval (300 seconds) is smaller than the average link down time (754 seconds). Thus, measures such as the number of links down observed at a reporting time are probably autocorrelated. Hence, care must be taken then when determining the size of the sampling interval when plotting these types of performance measures . If the sampling interval is large, small shifts might not be detected and any shifts will take longer to detect. If the interval is small, small shifts may be detected and shifts can be detected faster, but the data may be autocorrelated. This possible autocorrelation is not accounted for by conventional control charts and runs rules, therefore requiring the use of special procedures outlined by Montgomery (18:341-51). This issue of sampling interval and autocorrelation will be investigated during the case study where the actual repair rate will be known.

3.1.1.3 X-bar and R Chart Performance Measures. X-bar and R charts will be used to chart the following performance measures: number of links down,

DwnLnk, proportion of operating paths, **p-path,** and **Availability** = proportion of link uptime (calculated hourly and daily for each link).

3.1.2 XmR Charts.

These individual measurements charts are designed for use when the sample size is one (18:241). This sample size can occur when data is collected periodically or when the data just cannot be subgrouped for some reason. Here each data value is uniquely identified with a specific period of time and the frequency of collection is fixed. If the sample size is increased to more than one, this could create non-homogeneous samples that represent more than one time period (28:217). The non-homogeneity of the samples then depend on the homogeneity between time periods. If the time periods cannot be grouped together, XmR charts are required.

The control limits for the X chart are computed as:

$$CL = \bar{x} + 3\frac{\overline{mR}}{d_2}$$
$$CL = \bar{x}$$
$$LCL = \bar{x} - 3\frac{\overline{mR}}{d_2}$$

where d_2=1.128 for a moving range of n=2. (see Appendix A) So, the control limits are simplified to:

$$CL = \bar{x} + 2.66\overline{mR}$$
$$CL = \bar{x}$$
$$LCL = \bar{x} - 2.66\overline{mR}$$

The control limits for the mR chart are computed as:

$$CL = \overline{mR}D_4$$
$$CL = \overline{mR}$$
$$LCL = \overline{mR}D_3 = 0$$

$$mR_i = |x_i - x_{i-1}|$$

where $\qquad D_3 = 0 \qquad$ for n=2.(18:242-3)

$$D_4 = 3.267$$

3.1.2.1 XmR Chart Performance Measures. The XmR charts will be used with the measures: **Availability, Time Between Failures (TBF), Time to Failure (TTF),** and **Time to Repair (TTR)** (each described for X-bar charts above), **Mean Time Between Failures (MTBF), Mean Time to Failure (MTTF),** and **Mean Time to Repair (MTTR)** (calculated over all past failures after each failure/repair occurs), and **SSA** = steady-state availability (calculated for each link individually after each repair).

3.1.3 P Charts.

This chart is also called the Fraction Nonconforming chart. The fraction nonconforming per sample is just:

$$\hat{p} = \frac{number\_of\_nonconforming\_items\_in\_a\_sample}{total\_number\_of\_items\_in\_a\_sample}$$

It is customary to work with the fraction nonconforming, but the fraction conforming can be used just as easily if desired (18:148). The p chart is based on a count from a binomial distribution. This means that the each item in a sample of n items is classified as either conforming or nonconforming to a specification. The count of units nonconforming in a sample, D, has a binomial distribution with parameters n, sample size, and p, probability

of a unit nonconforming (or fraction nonconforming) (18:148). This implies that the value of p is the same for all n items in any one sample.

This binomial probability model may be used when, according to Wheeler and Chambers (28:260), four conditions are satisfied:

1. The sample size for count D consists of n distinct items.
2. Each of the n distinct items are classified as either conforming or nonconforming.
3. The count, D, is the count of the number of items in the sample nonconforming.
4. Counts are independent of each other. The preceding item's conformance/nonconformance does not affect the following item's classification.

If these four conditions are not satisfied, the p chart should not be used. An XmR chart could be used instead.

If the binomial model is deemed appropriate, the mean (μ) and standard deviation (σ) of a binomial count are defined as (28:261):

$$\mu = np$$

$$\sigma = \sqrt{np(1-p)}$$

where n = sample size and p is the theoretical fraction nonconforming. Alternately, the mean (μ) and standard deviation (σ) of the sample fraction nonconforming, p-hat, are defined as (18:148):

$$\mu = p$$

$$\sigma = \sqrt{\frac{p(1-p)}{n}}$$

The control limits for the p chart when p is unknown are calculated as:

$$CL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$
$$CL = \bar{p}$$
$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$$

where
$$\bar{p} = \frac{\sum_{i=1}^{m} \hat{p}_i}{m}$$
$$\hat{p}_i = \frac{D_i}{n}$$

and m=sample number, n=sample size, D_i=number nonconforming in sample i. If the true fraction nonconforming, p, is known, it is used in the above limits in place of p-bar (18:148-50). This type of chart is useful when attributes of the system are of interest that are not easily represented numerically (such as a communication link's status as up or down). They can be easily monitored on a p chart.

3.1.3.1 P Chart Performance Measures. The p chart will be used with the measures: proportion of operating links, **p-up** (calculated at each 'state'), **p-down** (calculated at each 'state'), **p-path** (as described earlier), and **p-link** (calculated for each link individually at each 'state').

3.1.3.2 np Chart. This is a chart for the *number* nonconforming. This chart monitors the binomial count of units nonconforming, D,that is used to compute the *fraction* nonconforming above. Hence, the mean (μ) and standard deviation (σ) are those defined earlier for the binomial count with the following corresponding control limits when p is unknown (18:162):

$$CL = n\bar{p} + 3\sqrt{n\bar{p}(1-\bar{p})}$$
$$CL = n\bar{p}$$
$$LCL = n\bar{p} - 3\sqrt{n\bar{p}(1-\bar{p})}$$

where p-bar is defined above. As for the p chart, the theoretical fraction nonconforming, p, is used in the above limits in place of p-bar if it is known. Any of the binomial count performance measures can be plotted on this type of chart, such as the number of links down, **DwnLnk**.

3.1.4 Data Distribution.

There is a common belief that in order to use a control chart, the data must be normally distributed. This belief comes from the use of the tabulated constants used in control limit computations. The values for these constants are computed assuming a normal distribution, but these constants will not change appreciably when the data is not normal (28:65) Wheeler and Chambers conducted their own study which included six

different distributions including such 'heavy-tailed' distributions as the Exponential and Chi-Square (28:66). According to this study, "even wide departures from normality will have virtually no effect upon the way the control charts function in identifying uncontrolled variation" (28:76).

3.1.5 Trial Control Limits.

When the standards of the data's distribution are unknown, they must be estimated from sample data and used to compute trial control limits. It is common practice to collect 20 to 30 samples to calculate the trial limits, but it is not necessary if only limited amounts of data are available (28:45). These trial control limits are then applied to the sample data to determine if the process was in control when the sample data was collected. Montgomery goes on to say that if some of the sample data points plot outside of the control limits, they should be examined for an assignable cause (18:150). If one is found, the point is discarded from the trial control limits calculation. If no assignable cause is found, the point can either be discarded as having been drawn from a probability distribution characteristic of an out-of-control state, or it can be retained if the limits are deemed appropriate for current control. He also states that sometimes many of the sample data points plot outside of the control limits. In this case it is more productive to look for a pattern among these points rather than just exclude or include them all blindly (18:150). But Montgomery states in a later section of his book that if any of the preliminary samples plot outside of the trial control limits, the samples are simply discarded and revised control limits are then calculated (18:241). It is clear then that a set policy does not exist for discarding out of control points while calculating trial limits. In fact, Wheeler and Chambers state that, "Control limits ... will usually detect a lack of control when it exists even though the out-of-control points were used in the

computation" (28:226). Hence, any decision regarding the exclusion of points in the computation of trial control limits is up to the discretion of the user.

3.2 Data Simulation

3.2.1 Development of Simulation Model.

A simulation model was created to generate simulated data representing the sponsor's communication network. It was developed using the SLAM II simulation language in conjunction with user written FORTRAN inserts. The sole purpose for the simulation is to simulate data from the communication network that is currently unavailable. The main activities that are being simulated are the failure and repair of the links contained in the network. The rest of the simulation code collects and calculates statistics on these link failures and repairs. Path enumeration subroutines are adopted from Van Hove to enable the simulation to monitor the status of paths as well as those of links. These subroutines use a depth-first-search method on a tree representation of the network to enumerate all the paths from a source to a sink. (27:34-6,82-6)

Two important premises to modeling the network are:

(1) Information on times-to-failure and times-to-repair for each *individual* link is not available from the sponsor, instead

(2) only information on *overall* link performance is available (in the form of monthly summaries on the network as a whole), specifically:

- a link fails once every 169 seconds, and

- the average down time (repair time) for a link is 754 seconds.

On this basis it is assumed that:

(a) overall times between the failures of any two links are exponentially distributed with mean 169 seconds,

(b) each link is equally likely to fail when the process is in-control (i.e., when none of the links is in the process of degrading), and

(c) each link has the same down time distribution which is assumed to be exponential.

Given these additional assumptions, the simulation fails and repairs links using the following two steps:

(1) Link failure occurrence times are determined by repeated sampling from the overall time-between-failure distribution.

(2) At the time of a failure, the link having the failure is determined by choosing one of the 'up' links at random.

This second step is accomplished by sampling from a uniform distribution between 0 and the total number of links in the network (0, total links). The outcome corresponds to a link number in the network. The status of the link number chosen is then checked. If this link is already failed, a new draw from the uniform distribution occurs. This continues as necessary until a link number is chosen with a status of 'up'. This is valid as long as the process is in-control (i.e., all links are equally likely to fail). The structure of this logic is shown in the flowcharts in Figure 3.1. To model an out-of-control system (i.e., a link is degrading) requires an assumption be made about how a link degrades. For example, does a degrading link fail more often, have longer down time durations, have shorter times-to-failure, etc.. If a link is, say, five times as likely to fail as any other link, the uniform distribution for choosing a particular link could be altered to sample from (0, total links + 4) where the four 'extra' links will be assigned to the degrading link.

The simulation model is run on a 486/33 IBM compatible personal computer using SLAMSYSTEM Version 4.5 for Windows. This is a commercial version of SLAMSYSTEM that requires a 'Sentinel' attachment for the parallel port in order to provide extended storage space for large simulations. This hardware attachment is

obtainable only from Pritsker when purchasing the software (24). Microsoft FORTRAN Version 5.1 for DOS and Windows is also required to run the FORTRAN inserts. As written, the simulation creates approximately 12 MB of output files on the hard drive for one month of simulation. This is dependent on the size of the communication network inputted and can be controlled as needed by simply commenting out write statements in the FORTRAN code. A one month simulation takes approximately 20 minutes to run. All SLAM II and FORTRAN code are contained in Appendix E.
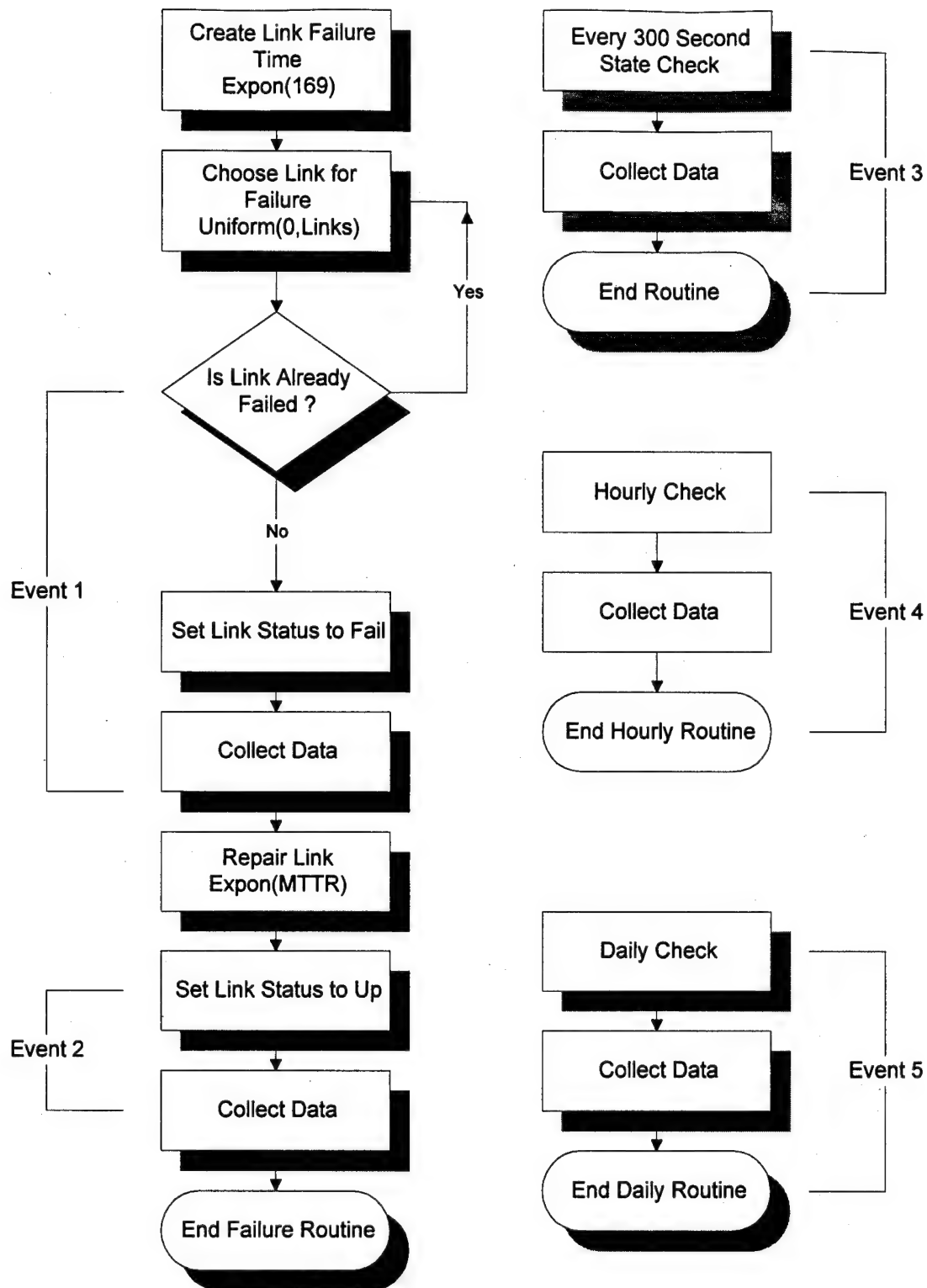
Figure 3.1 Continuous Link Failure Routine

3-15

3.2.2 Simulation Validation.

The basic simulation model can be validated by noting that, when in control, the simulated network behaves like an M/M/s queueing model with a finite calling population. (10:163-5) This representation can be realized by envisioning the links as 'customers' arriving at a repair facility wherein the times between arrivals are independently and identically distributed (iid) according to an exponential distribution, all down times are regarded as service times and are assumed to be (iid) according to an exponential distribution, and each link is assumed to have its own "repairman" (server). This last assumption can be made since 'down time' or 'service time' starts as soon as a link fails. This means that s, the number of servers, equals N, the number of links in the network (finite calling population). The rate diagram for this model is shown in Figure 3.2.
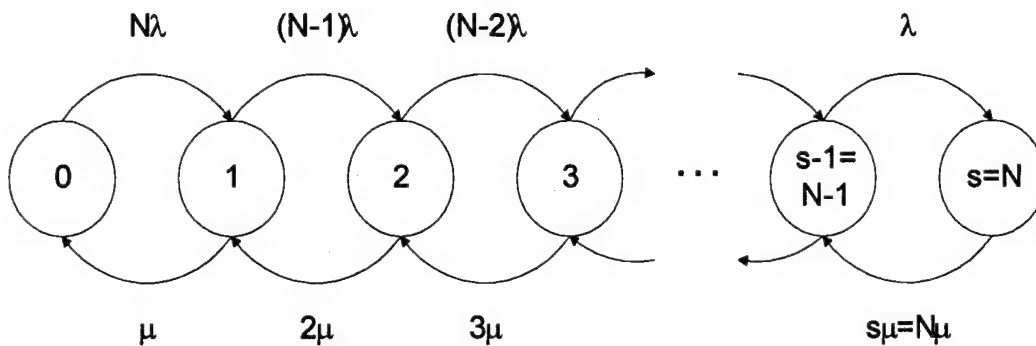
Figure 3.2 Rate diagram for M/M/s model with finite calling population (N=s)

The average arrival rate over the long run, (λ_bar), is the reciprocal of the mean of the overall time-between-failure distribution (derived from the monthly summaries on the

network earlier - 1/169 seconds). Also derived from the monthly summaries on the network is the mean service rate per busy server or repairman (μ), which is the reciprocal of the mean of the exponential down time distribution (1/754 seconds). The mean arrival rate per link (λ) can be derived using these two rates, (λ_bar) and (μ), and the steady-state equations for the M/M/s queueing model (10:152,164-5). This derivation is shown in Appendix B.

Initial validation of the model uses a four-node, five-link network shown in Figure 3.3 where λ_bar=1/169 seconds and μ=1/120 seconds (a larger value of μ is used in this small validation network to preclude links from failing at a faster rate than they are repaired hence, rendering an almost constant all links down condition). Using these rates, the steady-state equations in Appendix B are solved for λ and the expected number of customers in the queueing system, L. The value obtained for λ is compared to each link's observed end-of-simulation MTTF (Mean Time to Failure) via $1/\lambda = MTTF$, and L is compared to the average number of links down (failed) during the simulation. The equations and computations for these values are shown in Appendix C.
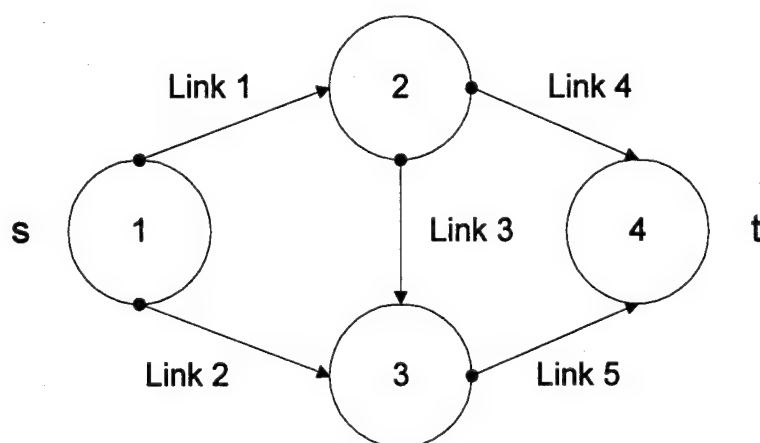
Figure 3.3 Validation Network

3-17

The simulation was run for 10 months in order to ensure steady state conditions were reached. The SLAM II Summary Report also shown in Appendix C contains the (steady-state) values of each link's MTTF and the average number of links down (failed) during the simulation for comparison the theoretical values of $1/\lambda$ and L. As can be seen, $1/\lambda$ and L agree quite well (within 0.002 links for L and an average of 4.4 seconds for $1/\lambda$) with their respective simulation values to show that the simulation model is valid. An additional cross check can also be made by looking at the means and standard deviations of the end-of-simulation sample MTBF (Mean Time Between Failure), sample MTTF (Mean Time to Failure), and sample MTTR (Mean Time to Repair) for each simulated link on the SLAM II Summary Report in Appendix C. The term sample meaning that the sample MTTF, for example, is estimated from the simulation data (i.e., not a theoretical value). The means and standard deviations should be close since these measures are supposed to be coming from exponential distributions. The summary report shows this cross check also validates the simulation.

3.2.3 Running the Simulation.

Once the simulation was validated using the 4-node, 5-link network, the case study communication network was inputted and run to obtain the needed data. This network has 41 nodes and 77 links and is shown in Figure 3.4 . Table 3.1 shows the link number assignments of this network. The required input file describing network topology for the path enumeration subroutines is shown in Appendix F. This file must contain the total number of nodes, total number of links, and each link's origin and destination node pair along with it's corresponding link number assignment. The node labeled as '1' is assumed to be the source node (s) and the node labeled with the total number of nodes (41 in this case study) is assumed to be the sink node (t). See Appendix F for proper

3-18
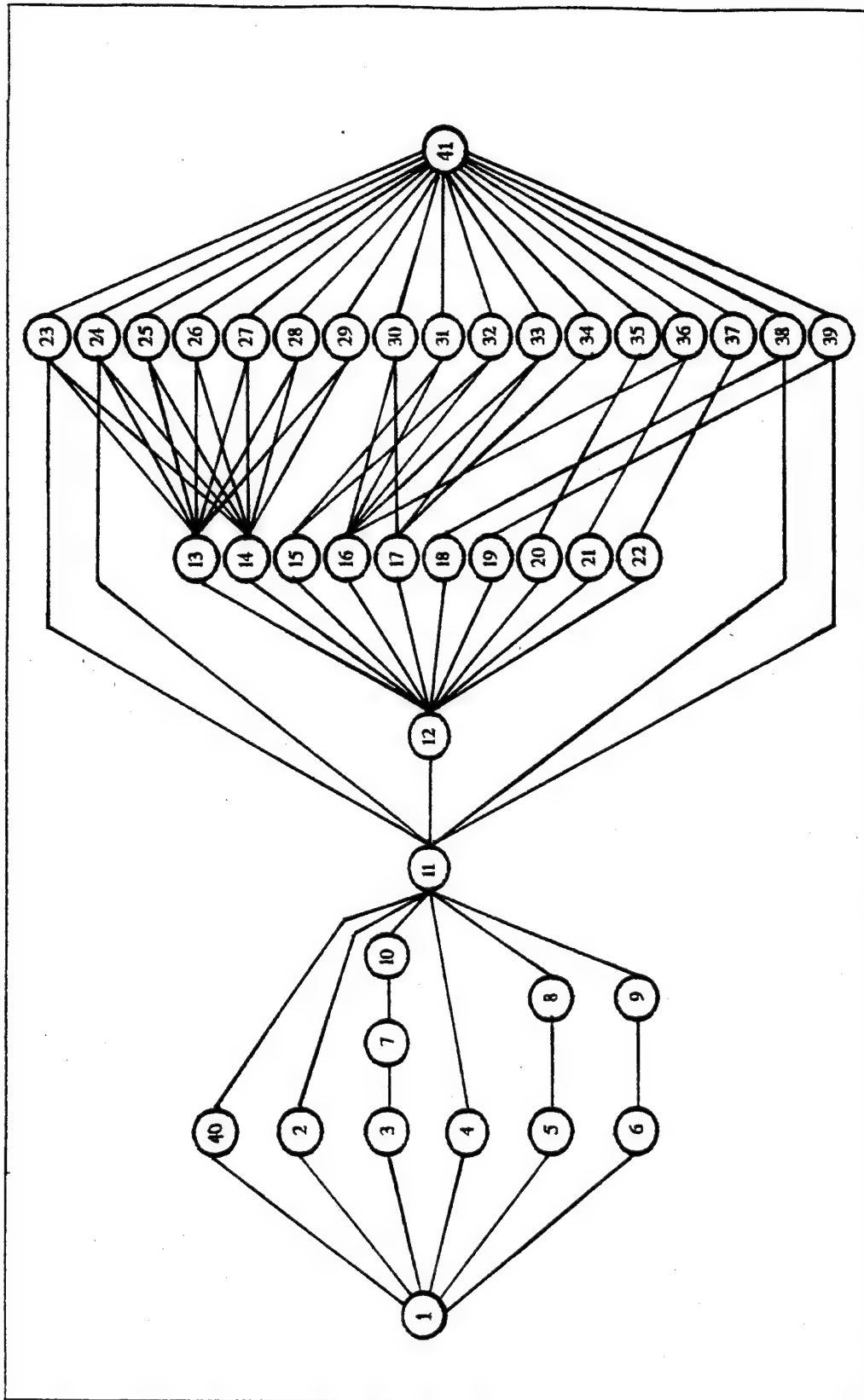
Figure 3.4 Case Study Network

Table 3.1 Case Study Network - Link Number Assignments

Origin Node	Destination Node	Link Number	Origin Node	Destination Node	Link Number
1	40	55	14	23	33
1	2	56	14	24	34
1	3	57	14	25	35
1	4	58	14	26	36
1	5	59	14	27	37
1	6	60	14	28	38
40	11	1	14	29	39
2	11	2	15	31	40
3	7	3	15	32	41
4	11	4	16	30	42
5	8	5	16	31	43
6	9	6	16	32	44
7	10	7	16	33	45
8	11	8	16	36	46
9	11	9	17	30	47
10	11	10	17	33	48
11	23	11	17	34	49
11	24	12	18	38	50
11	12	13	19	39	51
11	38	14	20	35	52
11	39	15	21	36	53
12	13	16	22	37	54
12	14	17	23	41	61
12	15	18	24	41	62
12	16	19	25	41	63
12	17	20	26	41	64
12	18	21	27	41	65
12	19	22	28	41	66
12	20	23	29	41	67
12	21	24	30	41	68
12	22	25	31	41	69
13	23	26	32	41	70
13	24	27	33	41	71
13	25	28	34	41	72
13	26	29	35	41	73
13	27	30	36	41	74
13	28	31	37	41	75
13	29	32	38	41	76
			39	41	77

format and also for output from the path enumeration subroutine for this case study. The sponsor approved this network as an acceptable sample network. The values for the overall mean time between link failures (average arrival rate over the long run) ($\lambda\_bar=1/169$ seconds) and the mean down time ($\mu=1/754$ seconds) are the same values obtained earlier from the data provided by the sponsor.

Upon running the simulation, steady state is approximated by the end of the first month. Again, the steady state equations in Appendix B are solved for λ and L. These theoretical values are then compared to their respective sample values from the simulation as shown for the validation network. This comparison again validates the simulation and is shown in Appendix D.

Finally, three items of concern were raised during the building and running of the simulation that are worthy of attention. First, there is a distinct difference between the terms MTBF (Mean Time Between Failure) and MTTF (Mean Time to Failure). MTBF is the time from the failure of an equipment until the equipment fails again (including the repair time), while MTTF is the time from the end of the last repair until the next failure. One needs to be sure which term is being used when comparing these time to the failure and repair rates. Second, multiple runs of the simulation are not necessary since the only purpose of the simulation is to obtain *example* data of a hypothetical communication network. Third, the issue of an initial transient period in the data is not a problem since the probability of being in the initial state, P_0, is on the same order as the probabilities of being in any of the other 10 most probable states (see Appendix D). Thus, we can expect the data obtained from the simulation to be consistent with that which might be observed in the long run from the actual communication network when it is operating in-control.

3.3 Summary

The methods for using the selected control charts have been reviewed along with the performance measures which will be investigated on each type of chart. Also, the simulation model used to obtain sample data was discussed. The results of plotting each of these performance measures are discussed in the next chapter.

4. Case Study Results

This chapter evaluates the identified performance measures and their applicable control charts for appropriateness in monitoring a communication network. This is facilitated through a case study that is developed using the simulated network shown in Figure 3.4. Each of the measures for the three monitoring viewpoints outlined in Chapter 2 will be discussed. The procedures in Chapter 3 for proper control chart construction are incorporated into EXCEL spreadsheets and macros that expand on the work of Horton (11:B-1). These EXCEL spreadsheets and macros are used extensively to complete the case study and automate the various control procedures for the sponsor. Once appropriate charts have been evaluated, recommendations on establishing Level of Service (LOS) Agreement specifications will be discussed.

4.1 Overall Network Performance Measures

Three measures were identified as potential indicators of overall network performance. These are number of links down (DwnLnk), proportion of operating links (p-up), and proportion of links down (p-down). First, the expected values of these measures for an in-control network are derived for use in developing control charts based on standards, followed by a demonstration of the use of these charts, especially for monitoring network degradation.

4.1.1 Theoretical Considerations.

As stated earlier in Chapter 3, the simulation model can be viewed as a representation of an M/M/s queueing model with a finite calling population. The steady

state equations for this model are presented in Appendix B. In these equations, L = 4.46 is the long run expected number of links down (failed). This is the theoretical and unconditional mean for the number of links down, DwnLnk, in the long run. Since there are 77 links in the network (sample size), L / 77 is the expected proportion of links down in the long run which equivalently represents the probability that that a specific link will be down at some arbitrary point in time. Given this framework, the number of links that will be down whenever the state of the network is observed can be modeled as a binomial random variable with parameters n = 77 and p = L / 77 = 4.46 / 77 (see conditions for using the binomial probability model in Section 3.1.3). The parameters n and p can then be used to compute the theoretical means of p-down = DwnLnk / 77 and p-up = 1 - p-down which, in turn, results in the following control limits for the three overall network performance measures.

np chart for DwnLnk:

$$\mathbf{UCL} = np + 3\sqrt{np(1-p)} = 4.46 + 3\sqrt{4.46\left(1 - \frac{4.46}{77}\right)} = \mathbf{10.6094}$$

$$\mathbf{CL} = np = 77\left(\frac{4.46}{77}\right) = \mathbf{4.46}$$

$$\mathbf{LCL} = np - 3\sqrt{np(1-p)} = 4.46 - 3\sqrt{4.46\left(1 - \frac{4.46}{77}\right)} = -1.6894 \equiv \mathbf{0}$$

p chart for p-down:

$$\mathbf{UCL} = p + 3\sqrt{\frac{p(1-p)}{n}} = \left(\frac{4.46}{77}\right) + 3\sqrt{\frac{\left(\frac{4.46}{77}\right)\left(1 - \frac{4.46}{77}\right)}{77}} = \mathbf{0.1378}$$

$$\mathbf{CL} = p = \frac{4.46}{77} = \mathbf{0.0579}$$

$$\mathbf{LCL} = p - 3\sqrt{\frac{p(1-p)}{n}} = \left(\frac{4.46}{77}\right) - 3\sqrt{\frac{\left(\frac{4.46}{77}\right)\left(1 - \frac{4.46}{77}\right)}{77}} = -0.0219 \equiv \mathbf{0}$$

and p chart for p-up:

$$\mathbf{UCL} = (1-p) + 3\sqrt{\frac{(1-p)p}{n}} = 1 - \left(\frac{4.46}{77}\right) + 3\sqrt{\frac{\left(1 - \frac{4.46}{77}\right)\left(\frac{4.46}{77}\right)}{77}} = 1.022 \equiv 1$$

$$\mathbf{CL} = 1 - p = 1 - \frac{4.46}{77} = 0.9421$$

$$\mathbf{LCL} = (1-p) - 3\sqrt{\frac{(1-p)p}{n}} = 1 - \left(\frac{4.46}{77}\right) - 3\sqrt{\frac{\left(1 - \frac{4.46}{77}\right)\left(\frac{4.46}{77}\right)}{77}} = 0.8622$$

Hence, the standards for all three of these performance measures' distributions are known (for the case study network model) and do not need to be estimated from the sample data in order to compute the control limits. Notice that the value for the count cannot be less than 0 and the proportions must be between (or equal to) 0 and 1 (and so must their corresponding control limits for them to be meaningful).

4.1.2 Autocorrelation of Data Points.

As mentioned in Section 3.1.1.2, autocorrelation may exist between consecutive observations of the number of links down if the time between observations is short and especially if the data collection rate is faster than the repair rate of the links. The repair rate of the links for the case study network is 1/754 seconds; much slower than the collection rate of 1/300 seconds. Therefore, possible autocorrelation must be investigated. The number of links down is shown in time series plots using the collection rates of 1/300 seconds, 1/15 minutes, 1/30 minutes, and 1/hr (chosen to compare a wide range of collection rates and for their even intervals to facilitate ease of data collection) in Figures 4.1 - 4.4. The first 96 observations of a one week period of data is charted for each collection rate. As the data collection interval gets larger, the evidence of patterns (autocorrelation) becomes less prominent.
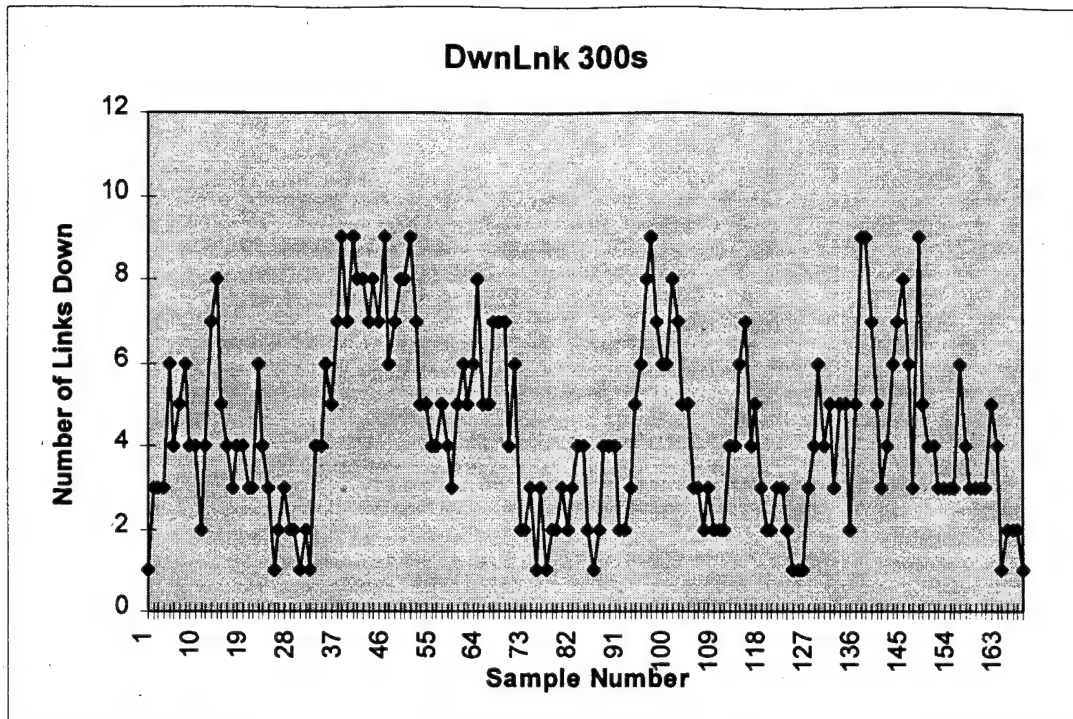
Figure 4.1 Time Series Plot of 1/300 sec DwnLnk Data
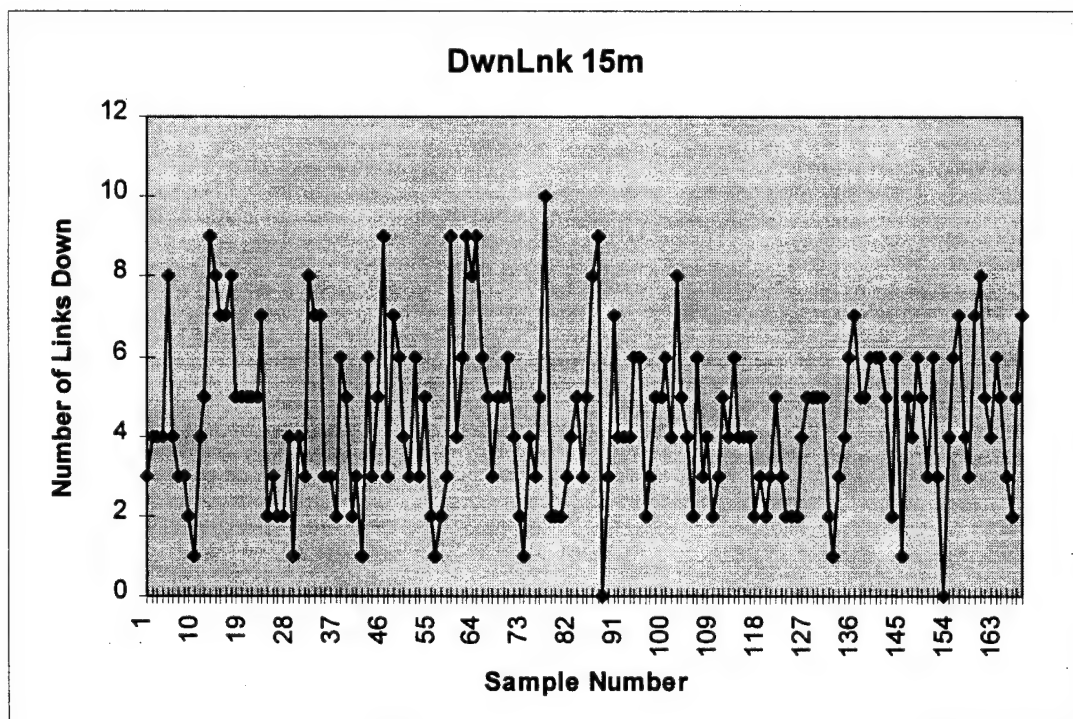
Figure 4.2 Time Series Plot of 1/15 min DwnLnk Data

4-4
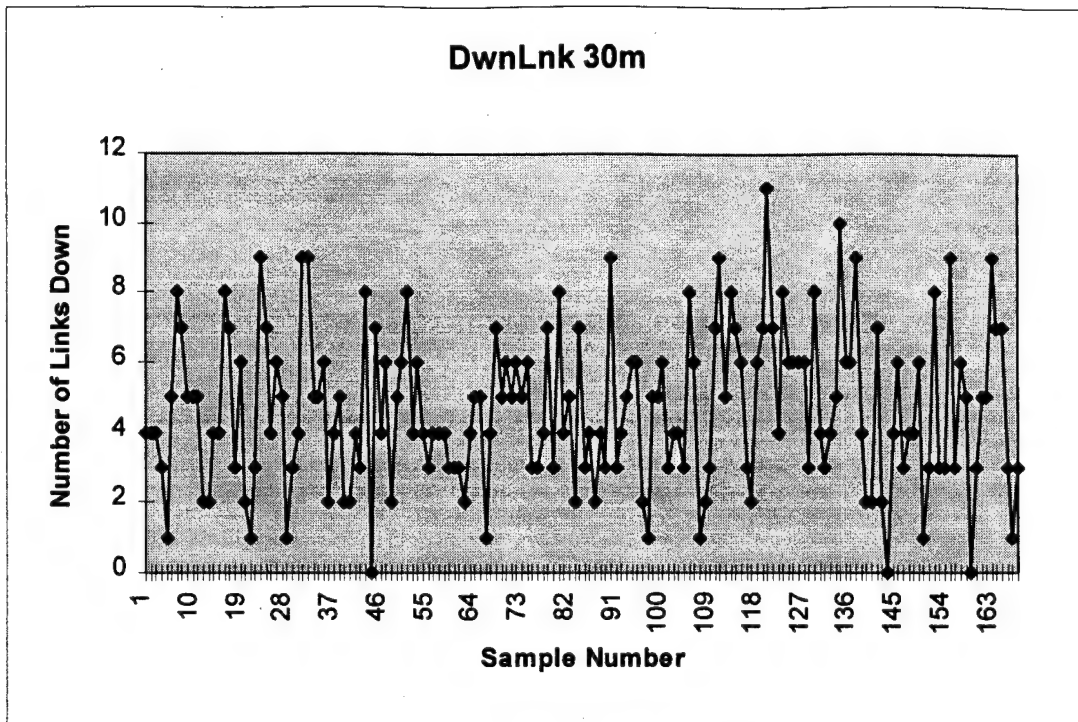
Figure 4.3 Time Series Plot of 1/30 min DwnLnk Data
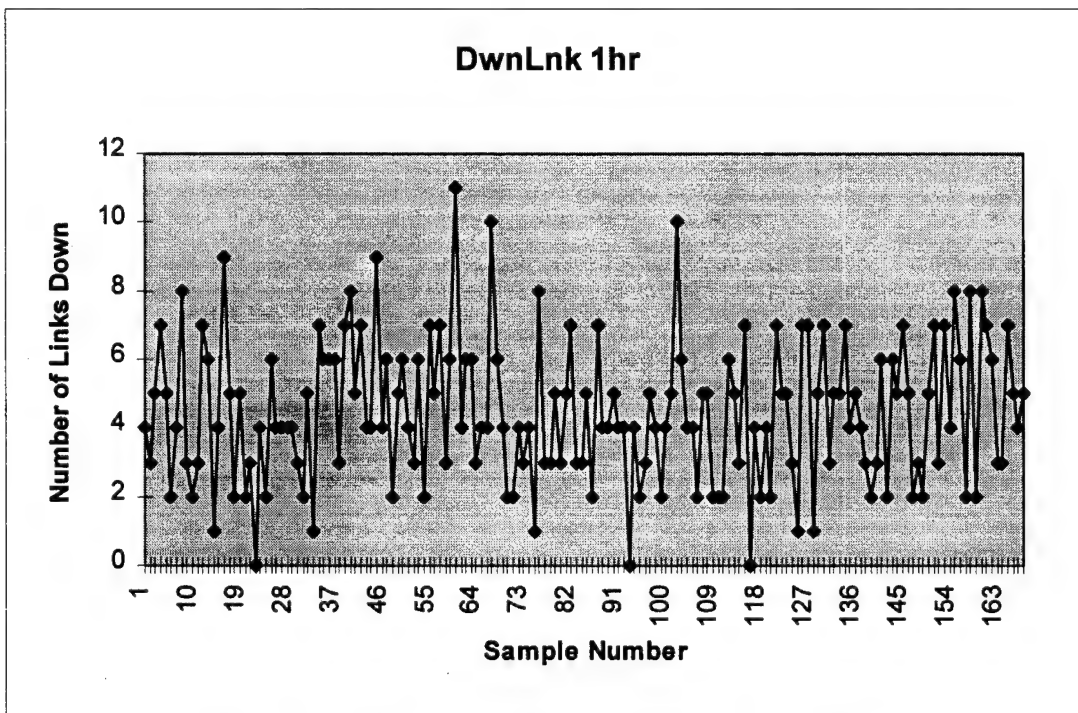
Figure 4.4 Time Series Plot of 1/hr DwnLnk Data

One week of data for the Measure DwnLnk was then tested for autocorrelation at lag 1 using the software package STATISTIX Version 4.0 (26). This software uses the computations for the estimate of the autocorrelation function at lag k from Box and Jenkins shown below (5:26-32):

$$r_k = \frac{\frac{1}{N} \sum_{t=1}^{N-k} (z_t - \bar{z})(z_{t+k} - \bar{z})}{\hat{\sigma}_z^2}$$

where the data observations are $z_1, z_2, \ldots z_N$ and:

$$\bar{z} = \frac{1}{N} \sum_{t=1}^{N} z_t$$

$$\hat{\sigma}_z^2 = \frac{1}{N} \sum_{t=1}^{N} (z_t - \bar{z})^2$$

To test whether an observed r_k value is significantly different from zero (i.e., to test whether the theoretical autocorrelation at lag k is zero, $\rho_k = 0$), Makridakis outlines a standard error formula for random data. If the data is truly random (not autocorrelated), 95% of the sample-based autocorrelation coefficients should lie between the limits (16:367-9):

$$-1.96(1/\sqrt{n}) \leq r_k \leq 1.96(1/\sqrt{n})$$

Hence, this can be used as a rough guideline for determining if the autocorrelation is present or not. The autocorrelation values for all three performance measures were identical since they all are functions of the number of links down. These values are shown in Table 4.1 with their corresponding limits.

Table 4.1 Autocorrelation for Overall Performance Measures (1 week of data)

Collection Rate	r_1	Limits	Sample Size	Autocorrelation
1/300 seconds	0.674	$-0.044 \leq r_1 \leq 0.044$	2016	significant
1/15 minutes	0.301	$-0.076 \leq r_1 \leq 0.076$	672	significant
1/30 minutes	0.047	$-0.107 \leq r_1 \leq 0.107$	336	no significant
1/hour	-0.044	$-0.151 \leq r_1 \leq 0.151$	168	no significant

From this autocorrelation information, collecting data either once every 30 minutes or once every hour should provide uncorrelated data points. One of these rates should be used if conventional control charts are to be used. If a faster collection rate is desired in order to detect process shifts sooner, special procedures are required as outlined in Montgomery (18:341-51). For this case study, the rate of 1/hr will be used for consistency.

4.1.3 Demonstration of Procedures

Each performance measure has an appropriate control chart(s) for monitoring it depending on the type of data each measure represents. The charts for each performance measure were identified in Chapter 3 and will be demonstrated here. Each chart in this section is shown with its control limits (UCL, CL, and LCL) and 1-sigma and 2-sigma warning limits. All limits in this section were computed in Section 4.1.1.

4.1.3.1 Down Links. The measure **DwnLnk** has two possible control charting techniques; np chart and x-bar and R charts. The np chart is shown in Figure 4.5. Applying the runs rules from Section 2.5.10 show that only one point on the np chart (Sample 60) is plotting out-of-control. Since it is known that there is not an

assignable cause for Sample 60 (there were no assignable causes built into the simulation), the process is concluded to be in-control. The samples were generated from the simulation which was designed to be in-control, hence the single out-of-control point is a chance occurrence due to the draw from the exponential distributions included in the simulation.
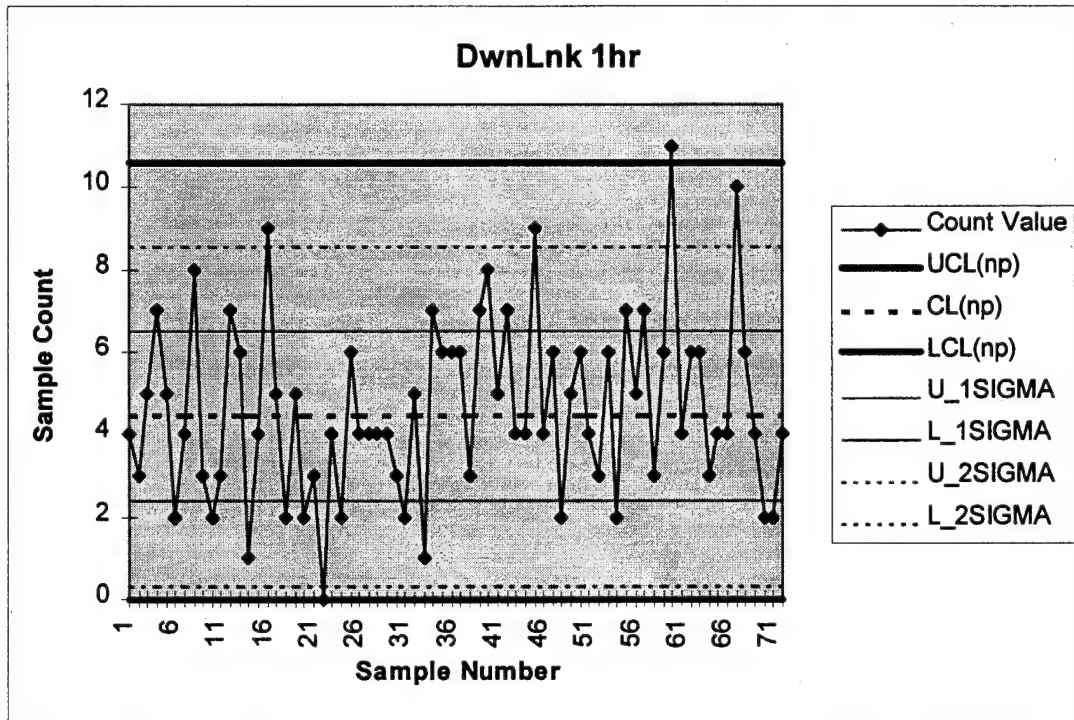
Figure 4.5 np Chart for DwnLnk (1/hr collection rate)

In actuality DwnLnk, the number of down links, is a time-persistent variable in the network that changes value whenever a link fails or is repaired (not necessarily at regular intervals). If this time-persistent data (instead of the 'snapshot' data taken at regular intervals) were plotted it would look similar to Figure 4.6.
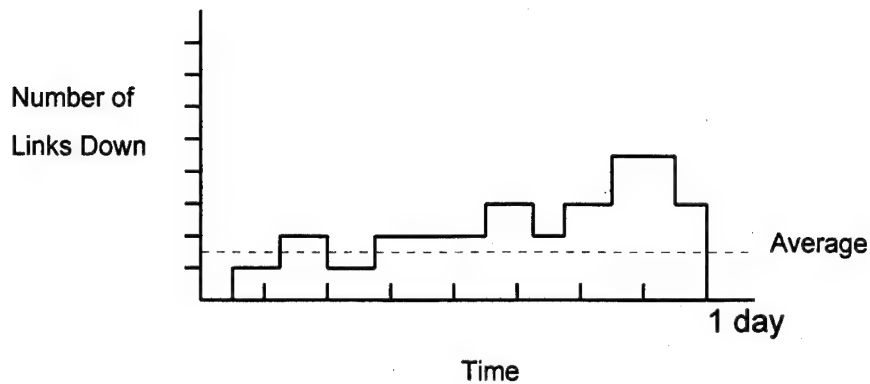
Figure 4.6 Behavior of Time-persistent Variable DwnLnk

This average of this data over a one day interval can be approximated by averaging the numbers observed at each hourly reporting time (the 1/hr DwnLnk data used for the np chart earlier). This new statistic for DwnLnk is then a reasonable surrogate for the average of the original time-persistent variable. Hence it is reasonable to use the 'snapshot' data in place of the time-persistent data if collection of the time-persistent data is, for example, too costly. The mean and variance (or range) of the average number of links down per day can then be estimated using the equations in Section 3.1.1 and subsequently used to compute the following control limits (1 month of hourly observations with a sample size of n = 24 were used for estimation).

x-bar chart for DwnLnk($A_2 = 0.157$ for n = 24):

$$\text{UCL} = \bar{\bar{x}} + A_2\bar{R} = 4.4139 + 0.157(7.8) = \mathbf{5.6402}$$

$$\text{CL} = \bar{\bar{x}} = \mathbf{4.4139}$$

$$\text{LCL} = \bar{\bar{x}} - A_2\bar{R} = 4.4139 - 0.157(7.8) = \mathbf{3.1876}$$

4-9

R chart for DwnLnk ($d_2 = 3.895$ and $d_3 = 0.712$ for $n = 24$):

$$UCL = \bar{R} + 3d_3 \frac{\bar{R}}{d_2} = 7.8 + 3(0.712)\left(\frac{7.8}{3.895}\right) = 12.0744$$

$$CL = \bar{R} = 7.8$$

$$LCL = \bar{R} - 3d_3 \frac{\bar{R}}{d_2} = 7.8 - 3(0.712)\left(\frac{7.8}{3.895}\right) = 3.5178$$

The x-bar and R charts are shown in Figure 4.7 and Figure 4.8. The hourly data is subgrouped into daily samples of size $n = 24$. Applying the runs rules to these charts show that two points (Sample/Day 10 and 21) on the x-bar chart and a run of 2 on the R chart (Days 17 and 18) are plotting out-of-control. Again, the samples were generated from the in-control simulation, so there is no assignable cause for the out-of-control points. Investigating Day 10 for demonstration purposes shows that this sample's 24 data points include 4 values of 6, 4 values of 7, 3 values of 8, and 2 values of 9. With a UCL value of 5.6402, half of the data points were above this limit. Examining the individual data points in each sample is helpful in detecting if the out-of-control point was caused by one or two unusual data points or if an actual shift in the mean did occur (18:212). Here, since some of Day 10's data points are unusually high, and since a trend toward high values of DwnLnk is not evident after Day 10, this out-of-control indication could be deemed the result of a random occurrence if the search for an assignable cause of the high values proves fruitless. This demonstrates how the x-bar chart detects a possible out-of-control condition and thus prompts a search for an assignable cause. As an example, the network monitor could search for an assignable cause for the high number of links down by investigating the 'conditions' of the network during Day 10. This could be accomplished by looking at the network controller's log for any unusual occurrences on Day 10. For instance, an electrical storm may have disrupted the network, or perhaps
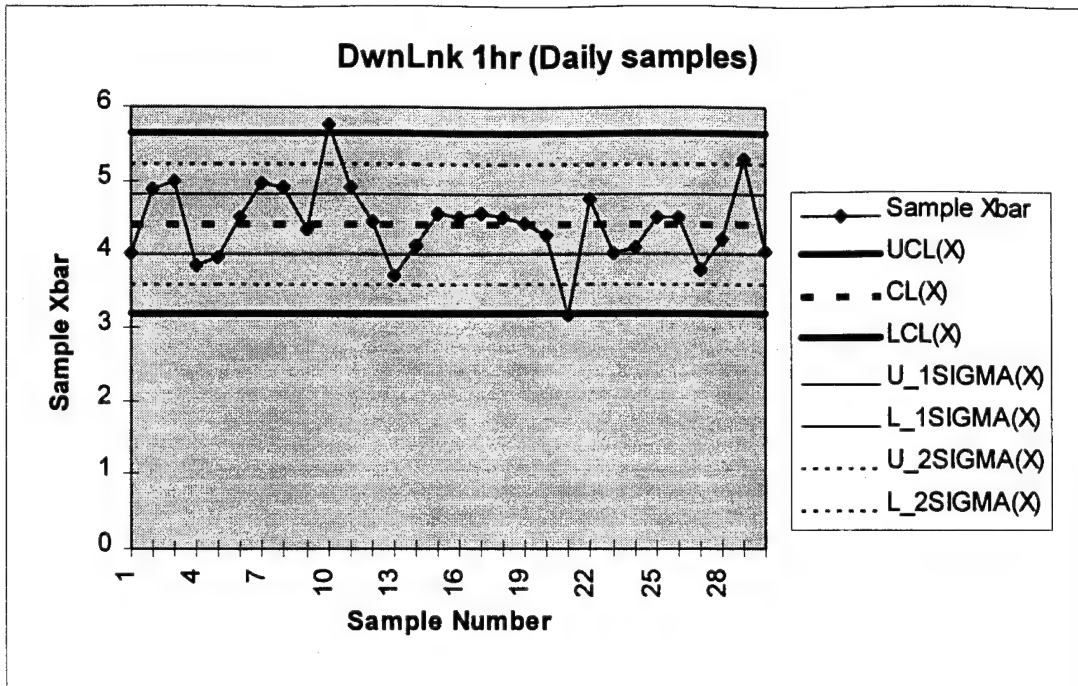
Figure 4.7 x-bar Chart for DwnLnk (1/hr collection rate - daily samples)
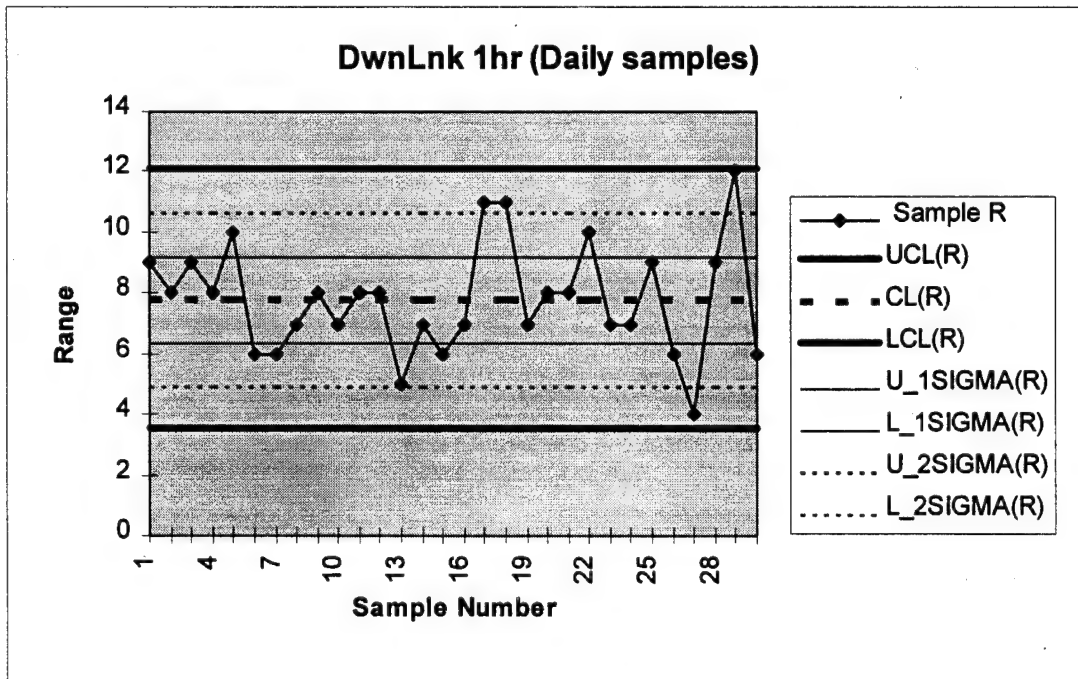
Figure 4.8 R Chart for DwnLnk (1/hr collection rate - daily samples)

4-11

there were unusually high traffic loads that caused links to fail more often. An investigation of this type could reveal obvious assignable causes like these, or could reveal a cause that would have been noticed because of the control chart's prompting.

Both the np chart and the x-bar and R chart techniques seem viable for monitoring the performance measure DwnLnk. The choice between them should be based on the desired rate of detection for out-of-control points. If a shift in the average number of links down needs to be detected in a matter of hours rather than days, the np chart should be used. Also, since the observations are grouped on the x-bar and R charts, they now represent a longer time interval and the samples are now comparing, for example, daily values instead of hourly values. Consequently, if hourly comparisons are desired when the data collection rate is 1/hr, the np chart is the logical choice. However, if daily comparisons are desired when the data collection rate is 1/hr, the x-bar and R charts should be chosen. One additional consideration before choosing is that x-bar and R charts aggregate data which could smooth out shifts and cause slower detection (or no detection at all for small shifts), but it also allows direct monitoring of the average number of links down in a day if that is a concern of the network. Alternately, the np chart plots the individual data points so that each measurement can be monitored directly and aggregation is not a concern.

4.1.3.2 Proportion of Operating Links. The measure **p-up** has one possible control charting technique; the p chart (although the technique above for averaging the counts of DwnLnk on an x-bar chart can also be applied to p-up [and also p-down in the next section], it will not be covered again for the sake of redundancy). The p chart is shown in Figure 4.9 (Figure 4.9 is shown with Figure 4.10 so that it can be more easily compared to p-down). Applying the runs rules show that only one point (Sample 60) is plotting out-of-control. This is the same out-of-control point identified on the np chart

4-12
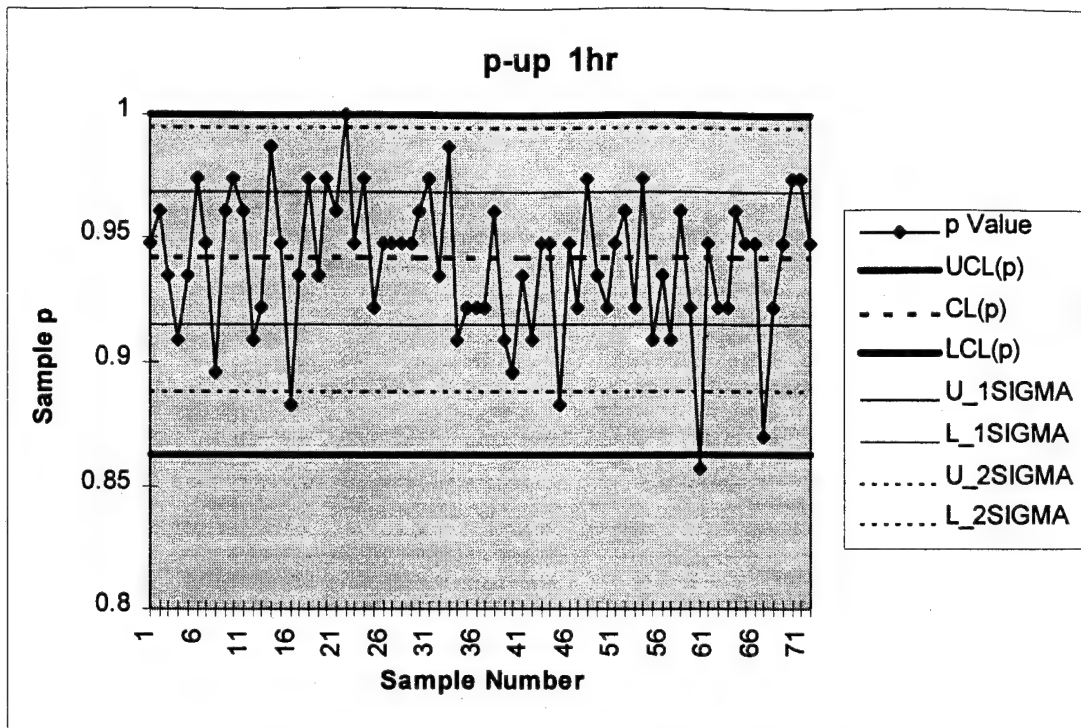
Figure 4.9 p Chart for p-up (1/hr collection rate)
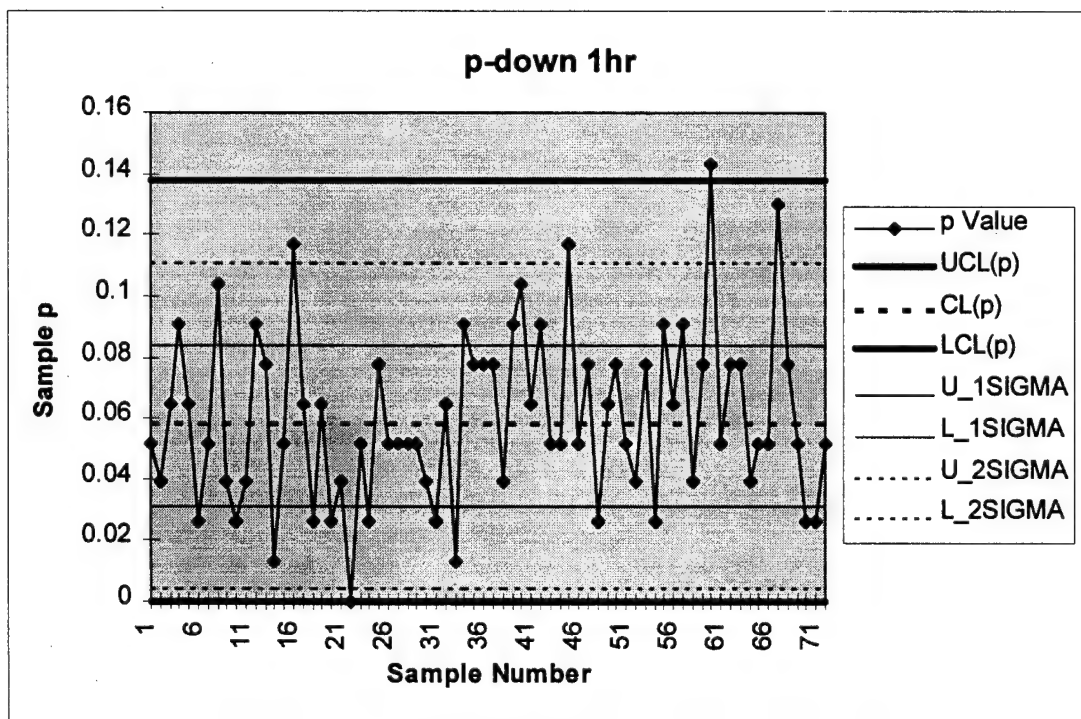
Figure 4.10 p Chart for p-down (1/hr collection rate)

4-13

for the measure DwnLnk. This is understandable since the value for DwnLnk is used in the computation of p-up. The high number of links down has lowered the overall link reliability resulting in an out-of-control indication. This chart is perfectly suited to monitor the performance measure p-up since this measure is based on the binomial count, DwnLnk, as demonstrated in Sections 3.1.3 and 4.1.1. Each individual data point is plotted, so there is no concern over aggregation of data.

4.1.3.3 Proportion of Links Down. The measure **p-down** also has one possible control charting technique; the p chart. This chart is shown in Figure 4.10. Once again applying the runs rules show that only one point (Sample 60) is plotting out-of-control. This is the same out-of-control point identified on both the np chart for DwnLnk and the p chart for p-up. This only makes sense since p-down is the antithesis of p-up. The high number of links down has raised the overall proportion of links down resulting in an out-of-control indication. This chart is also perfectly suited to monitor the performance measure p-down since this measure is also based on the binomial count, DwnLnk, as demonstrated in Sections 3.1.3 and 4.1.1. Here too, each individual data point is plotted, so again, there is no concern over aggregation of data. Comparing the p-down and DwnLnk charts (Figure 4.10 and Figure 4.5), it is easily seen that the p chart is just a 'rescaling' of the np chart. The plotted points in relation to their respective control limits are identical. Also comparing the p-down and p-up charts (Figure 4.10 and Figure 4.9), it is easily seen that these charts are a 'mirror image' of each other.

Therefore, since all three measures, DwnLnk, p-up, and p-down are so closely related, only one of them probably needs to be plotted by the sponsor. A choice between the measures will depend on what makes the most sense to the network controller/ monitor; a proportion of links up (p-up), a proportion of links down (p-down), or a simple count of the number of links down, DwnLnk.

4.1.4 Degradation Monitoring.

As stated in Section 2.3, degradation will be monitored by charting these and other performance measures. The three performance measures identified as indicators of overall network performance (DwnLnk, p-up, and p-down) can all be used as indirect measures of network degradation through the runs rules. The runs rules are designed to evaluate the entire sequence of points on a control chart, thereby enabling the chart to detect small shifts and decaying or degrading conditions. Where a single out-of-control point on a control chart should be investigated for an assignable cause, so too should a run of points satisfying the runs rules. Assuming that degradation of the network manifests itself as more links failing over time, a slow increase of DwnLnk and p-down or a slow decrease of p-up is an indication of degradation in the network. Also, an abrupt shifts can occur indicating an abrupt degradation rather than a slow decaying degradation. These patterns should be watched for on the control charts to monitor network degradation.

4.1.4.1 Degradation Case Study.
After the data was obtained for the in-control case study network, the simulation was reprogrammed to include a degradation. This degradation consisted of link number 13, in the same network (Figure 3.4 and Table 3.1) failing five times more often than each of the other links in the network. This degradation occurred abruptly and not slowly over time. This degradation case study will be followed through each of the three monitoring viewpoints using one of the measures from each viewpoint in an attempt to detect the degradation.

In this first viewpoint of the overall network measures, the degraded data is plotted for hourly p-down with the resulting p chart shown in Figure 4.11 . An important note here is that the control limits have already been computed from either known theoretical standards or from sample data from when the process is in-control, and the

4-15
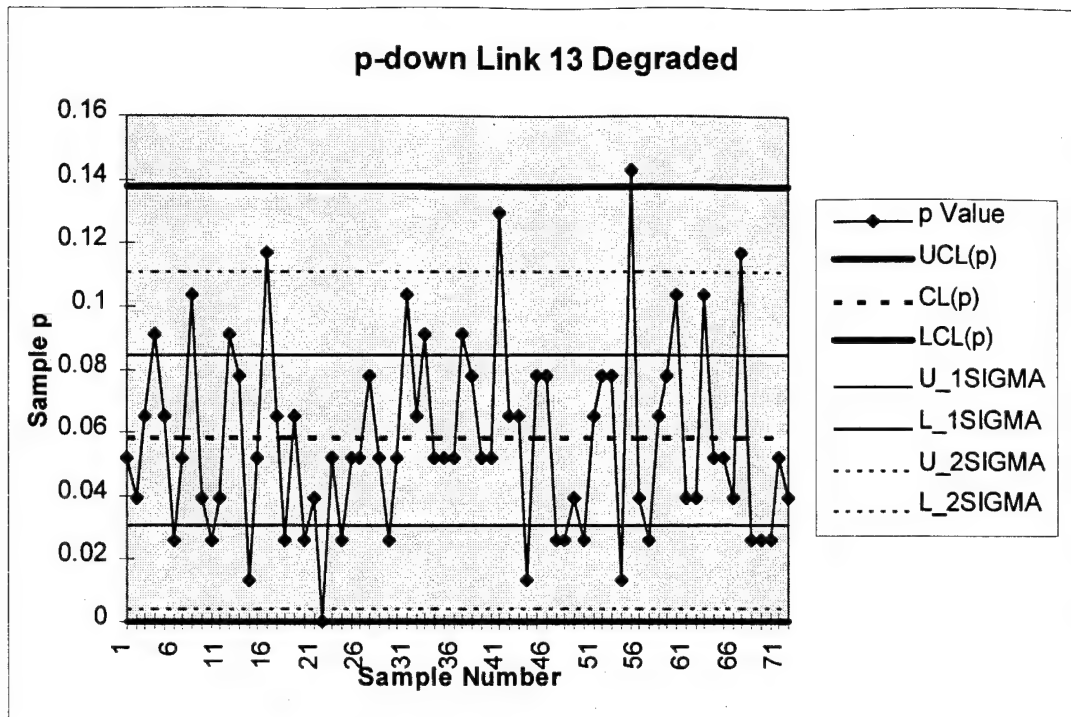
Figure 4.11 p Chart for p-down (Degraded Link 13)

new data is plotted on the already established chart. The degraded condition is that link

number 13 is failing five times as often as any other link with the overall time-between

failures for all links adjusted so as to keep the other links' individual time-to-failure equal

among all links except link number 13. This degradation occurred in Sample 25 and is

not detected by the chart. Hence, since p-down is measuring the proportion of down links

at any given time, no change should be seen from the degradation. Link 13 is failing

more often, but the other links are failing less often to keep the overall time-between-

failures the same. Therefore the proportion p-down will not indicate any shift. This is

supported by the p chart in Figure 4.11. This particular degradation cannot be monitored

using p-down since it, along with Dwn Lnk and p-up, are based on counts of the total

number of links down. If this count is not affected by the particular degradation, then

these measures will not detect the degradation. This reinforces the need to use more than

one performance measure to completely monitor the network.

4-16

4.2 (s-t) Performance Measures

One measure was identified as a potential indicator of network performance for a customer's (s-t) pair. This measure is the proportion of operating paths (p-path). For this case study, the source (s) is node 1 and the sink (t) is node 41 as shown in Figure 3.4. the choices for s and t were made for simplicity sake, but any two nodes can be chosen as long as they are renumbered as s = 1 and t = the highest numbered node in the network; this is required by the path enumeration subroutine) The path enumeration subroutine in the simulation identified 198 paths from s-t. These paths are shown in Appendix F. First, theoretical considerations of these of this measure will be discussed, followed by a demonstration and then degradation monitoring using this measure.

4.2.1 Theoretical Considerations.

The measure p-path appears to be a proportion based on a binomial count of the number of operational paths with parameters n and p. If this is true, then the parameter n = 198 (total paths) is known, but the parameter p is unknown since the 'theoretical average number of non-operational paths' is unknown. Consequently, the standards for this performance measure's binomial distribution are unknown (for the case study network model) and need to be estimated from the sample data. The parameter p is estimated from the sample data with p-bar:

$$\bar{p} = \frac{\sum_{i=1}^{m} D_i}{mn} = \frac{\sum_{i=1}^{m} \hat{p}_i}{m}$$

where m = number of samples observed, n = total number of paths, D_i is the number of non-operating paths in sample i (i = 1,2, ... , m), and p-hat$_i$ is the proportion of non-operating paths in sample i (18:149). Note that the measure used here, p-path, is the

4-17

proportion of operating paths. The value (1 - p-bar) is then used to calculate the estimated mean and standard deviation for use in calculating the appropriate control limits.

4.2.2 Autocorrelation of Data Points.

The measure p-path is collected at every 'state', so the autocorrelation of the data points is investigated for this new measure. Once again, collection rates of 1/300 seconds, 1/15 minutes, 1/30 minutes, and 1/hr were tested for autocorrelation at lag 1 using the software package STATISTIX Version 4.0 (26) and then tested using the 95% standard error limits. The results are shown in Table 4.2

Table 4.2 Autocorrelation for p-path (1 week of data)

Collection Rate	r_1	Limits	Sample Size	Autocorrelation
1/300 seconds	0.639	$-0.044 \leq r_1 \leq 0.044$	2016	significant
1/15 minutes	0.246	$-0.076 \leq r_1 \leq 0.076$	672	significant
1/30 minutes	0.085	$-0.107 \leq r_1 \leq 0.107$	336	no significant
1/hour	0.147	$-0.151 \leq r_1 \leq 0.151$	168	no significant

From this autocorrelation information, collecting data at the rates of once every 30 minutes, or once every hour should provide uncorrelated data points for conventional control chart usage. As was stated earlier, the rate of 1/hr will be used for consistency in this case study.

4.2.3 Demonstration of Procedures.

The charts identified in Chapter 3 for monitoring p-path will be demonstrated here. Each chart in this section is shown with its control limits (UCL, CL, and LCL) and 1-sigma and 2-sigma warning limits.

4.2.3.1 Proportion of Operating Paths. As stated in Section 4.2.1, the measure **p-path** appears to be a proportion based on a binomial count of the number of operational paths with parameters n and p. Even so, the measure has three possible control charting techniques; p chart, XmR charts and x-bar and R charts. For the p chart, p-bar (and 1- p-bar) and the corresponding control limits are calculated below. (1 month of hourly observations were used for estimation):

$$-\bar{p} = \frac{\sum_{i=1}^{m}(n - D_i)}{mn} = \frac{\sum_{i=1}^{m}(1 - \hat{p}_i)}{m} = 0.6976$$

p chart for p-path:

$$\mathbf{UCL} = (1 - \bar{p}) + 3\sqrt{\frac{(1 - \bar{p})\bar{p}}{n}} = 0.6976 + 3\sqrt{\frac{(0.6976)(0.3024)}{198}} = \mathbf{0.7955}$$

$$\mathbf{CL} = 1 - \bar{p} = \mathbf{0.6976}$$

$$\mathbf{LCL} = (1 - \bar{p}) - 3\sqrt{\frac{(1 - \bar{p})\bar{p}}{n}} = 0.6976 - 3\sqrt{\frac{(0.6976)(0.3024)}{198}} = \mathbf{0.5997}$$

The p chart is shown in Figure 4.12. Here the runs rules do not even have to be applied to this chart to see that many points are plotting out-of-control. Since this data was generated from an in-control network, this chart is either giving many out-of-control 'false alarms' or some other cause is responsible. If this were not known to be data from

an in-control process, this chart would clearly indicate an out-of-control network. It is possible that there is a very high amount of inherent variability in the network with regard to this performance measure. But then the question is asked, if there is so much inherent variability, why are the control limits so narrow? Remember, the control limits on this chart were calculated using standard estimated from the very data that is now plotted on them. A high amount of variability in the data will cause the control limits computed from this data to be wide. The XmR chart will help explain this problem and is therefore investigated next.
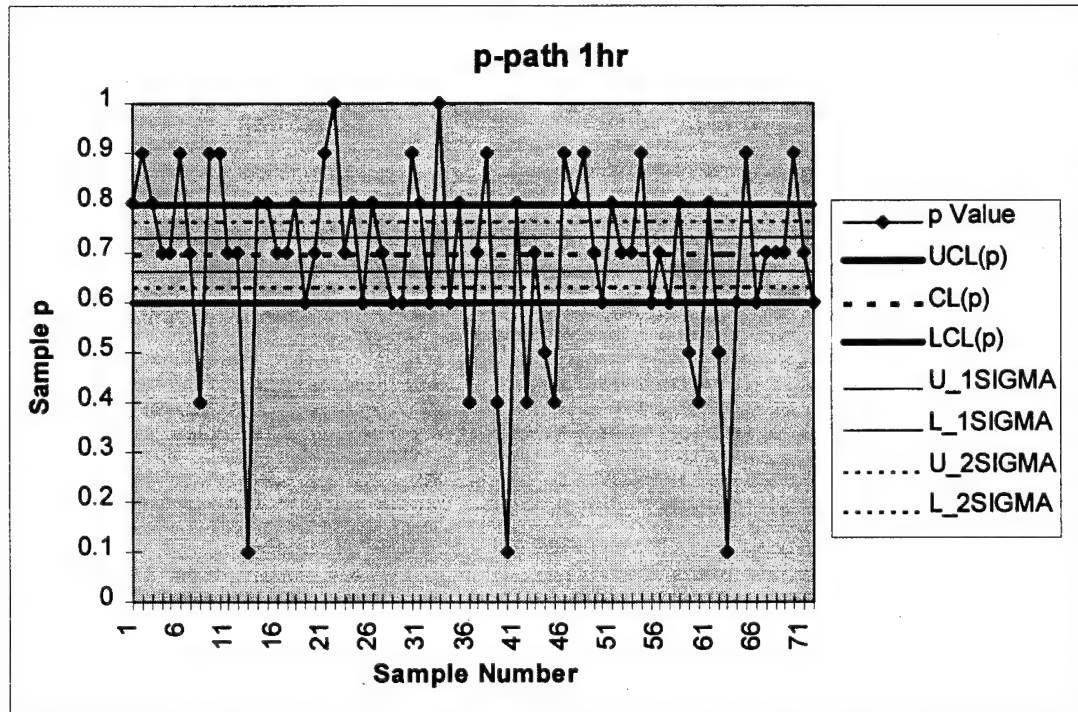
Figure 4.12 p Chart for p-path (1/hr collection rate)

For the XmR charts, the control limits also need to be calculated with estimated standards. This will be done assuming that the data is not from a binomial distribution for comparison to the p chart done earlier. One month of hourly observations were used for estimation of the standards for the control limits.

estimated standards for p-path:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_m}{m} = 0.6914$$

$$\overline{mR} = \sum_{i=1}^{m-1} mR_i = 0.2035$$

$$mR_i = \left| x_i - x_{i-1} \right|$$

where x-bar is the average of the individual proportions observed every hour, x_i, and m = 168. The control limits for the X chart are:

$$\textbf{UCL} = \bar{x} + 2.66\overline{mR} = 0.6914 + 2.66(0.2035) = 1.2327 \equiv \textbf{1}$$
$$\textbf{CL} = \bar{x} = \textbf{0.6914}$$
$$\textbf{LCL} = \bar{x} - 2.66\overline{mR} = 0.6914 - 2.66(0.2035) = \textbf{0.1502}$$

and the control limits for the mR chart are:

$$\textbf{UCL} = \overline{mR}D_4 = 0.2035(3.267) = \textbf{0.6648}$$
$$\textbf{CL} = \overline{mR} = \textbf{0.2035}$$
$$\textbf{LCL} = \overline{mR}D_3 = \textbf{0} \quad \text{always}$$

where

$$D_3 = 0$$
$$D_4 = 3.267$$

The XmR charts for p-path are shown in Figure 4.13 and Figure 4.14. Notice on the X chart how wide the control limits are, this seems to support the previous theory of a highly variable network in relation to p-path. Three points (Samples 13, 40, and 63) on the X chart and three points (Samples 14 and 41 along with Sample 13 as part of a '2 of 3' run) on the mR chart are plotting out-of-control. These 'spikes' in the mR chart correspond to the out-of-control points on the X chart as they should. Closely examining Samples 13, 40, and 63 on the X chart identifies that each has an adjacent point that is above or near the centerline. This causes the range computation between these sample points and their corresponding adjacent points to be large, hence the corresponding out-of control points on the mR chart. But even if there were no out-of-control points on the X chart, if on the X chart there was one point near the LCL and the next point was near the UCL, this variability should show up as a out-of-control point on the mR chart. This may indicate that the *variability* in p-path has shifted rather than the *mean* value. Searching for assignable causes for shifts in variability is just as important as searching for causes of shift in the mean. Out-of-control variability changes from time to time and is indicative of inconsistency and instability in the process that is being measured (28:7).

But in this case, the network seems to be inherently variable in relation to p-path, the number of operating paths. Referring to the case study network in Figure 3.4 and Table3.1, it is noted that there are some links in the network that are more 'important' than other links; important meaning that more paths depend on this link to operate. For example, if link number 13 (between nodes 11 and 12) fails, all paths connecting through nodes 13 to 22 and 25 to 37 will be down. This seems to make link number 13 a 'critical' link in the network and its failure in conjunction with other link failures could be exactly the situation that is causing the extremely low out-of-control points on the X chart. A search for an assignable cause could certainly reveal such an overt problem.
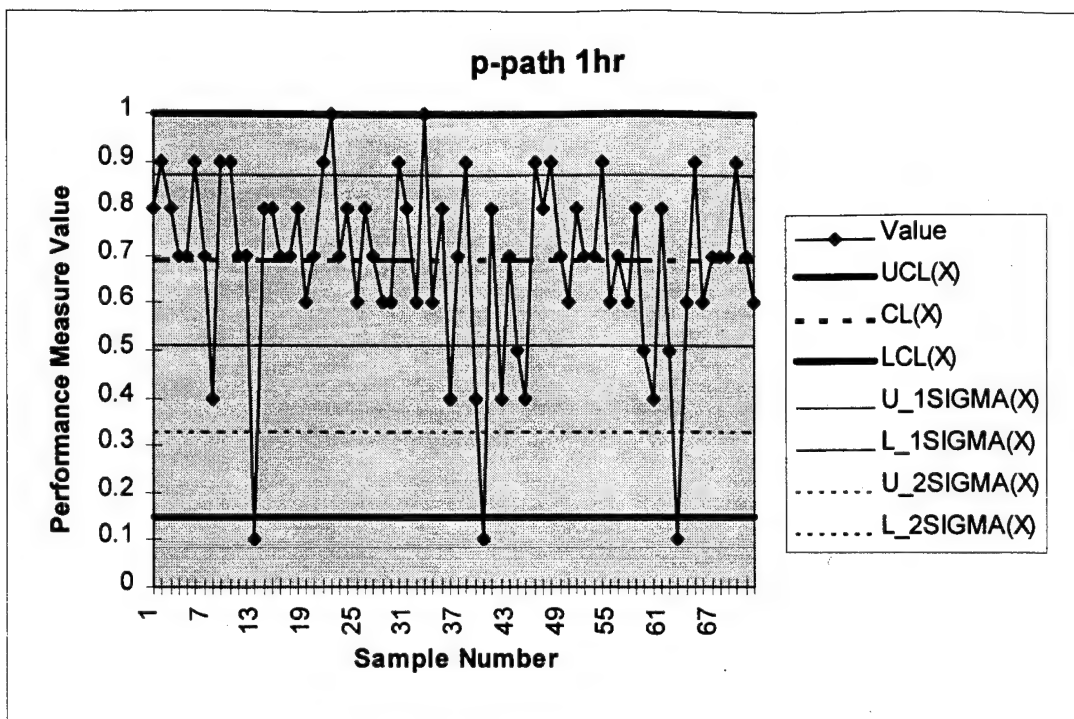
Figure 4.13 X Chart for p-path (1/hr collection rate)
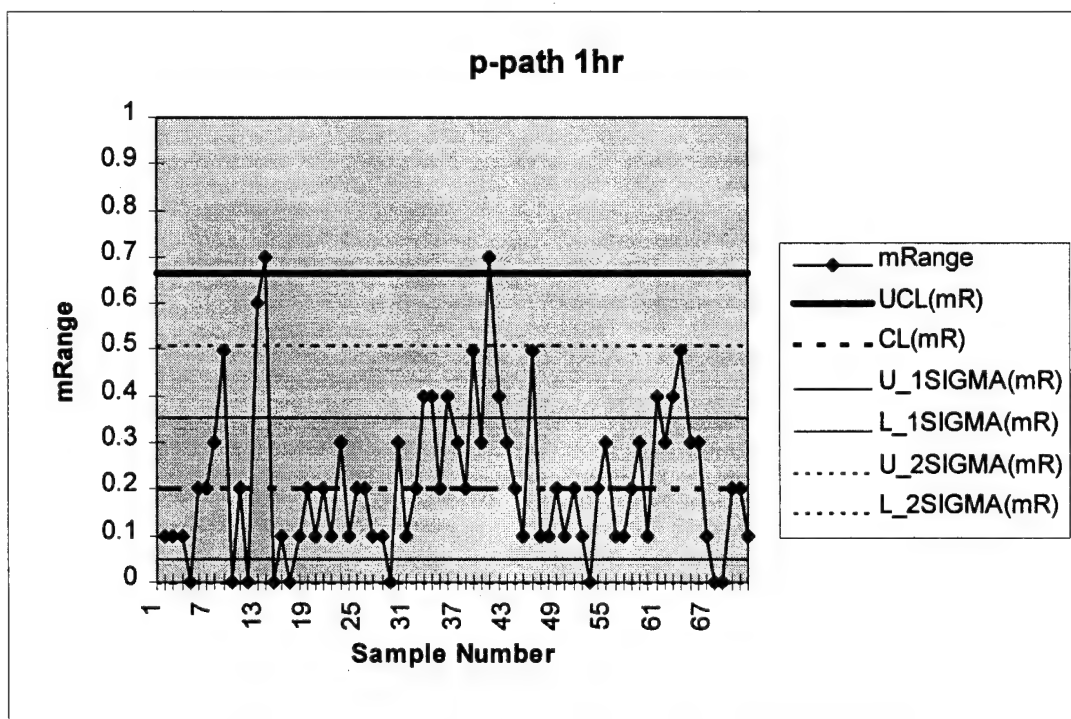
Figure 4.14 mR Chart for p-path (1/hr collection rate)

Examining the data from the simulation reveals that during the one hour period before Sample 13's collection (the hourly data collection occurs at the end of the hour), the following 'important' links failed: 9 (2 times), 11, 13, 14, 18, 25 and 60. Referring again to Figure 3.4 and Table3.1, any combination of these links failing together could have a devastating effect on the number of paths operating. The same such information surfaced for Samples 40 and 60, and all three of the one hour periods preceding the out-of-control samples contained a failure for link number 13, a critical link as mentioned earlier. So if such a drastic condition of the network is possible through the failure of just one link, the measure p-path will be highly variable with wide control limits as seen in the X chart. But back now to the p chart attempted earlier.

If the measure p-path is showing so much variability, why is it not showing up in the control limits on the p chart? Recall the conditions necessary for a binomial probability model to be appropriate from Section 3.1.3. Although the measure p-path seems well suited to monitoring on a p chart, it violates an assumption of the binomial probability model. This assumption requires that p is the probability that *any* 'unit' will not conform. This implies that the value of p is the same for all n 'units' in a sample. For p-path a 'unit' is a path, and the paths are not necessarily independent from one another. This is so since each path may contain different numbers of links and some paths may contain common links. As a result, p-path is not a proportion based on a binomial count and should not be monitored on a p chart. As Wheeler and Chambers state, If the binomial probability model is not appropriate, an XmR chart should be used instead of a p chart (28:260).

For the x-bar and R charts, the standards are again estimated and used to compute the control limits below (1 month of hourly data subgrouped into m = 30 daily samples, n = 24, was used for estimation and plotting):

$$\bar{\bar{x}} = \frac{\bar{x}_1 + \bar{x}_2 + \cdots + \bar{x}_m}{m} = 0.6914$$

$$\bar{R} = \frac{R_1 + R_2 + \cdots + R_m}{m} = 0.783$$

$$R_m = x_{max} - x_{min}$$

The control limits for the x-bar chart are:

$$\text{UCL} = \bar{\bar{x}} + A_2\bar{R} = 0.6914 + 0.157(0.7833) = \mathbf{0.8145}$$
$$\text{CL} = \bar{\bar{x}} = \mathbf{0.6914}$$
$$\text{LCL} = \bar{\bar{x}} - A_2\bar{R} = 0.6914 - 0.157(0.7833) = \mathbf{0.5682}$$

where A2 = 0.157 for n = 24.

The control limits for the R chart are:

$$\text{UCL} = \bar{R} + 3d_3\frac{\bar{R}}{d_2} = 0.7833 + 3(0.712)\left(\frac{0.7833}{3.895}\right) = 1.2129 \equiv$$
$$\text{CL} = \bar{R} = \mathbf{0.7833}$$
$$\text{LCL} = \bar{R} - 3d_3\frac{\bar{R}}{d_2} = 0.7833 - 3(0.712)\left(\frac{0.7833}{3.895}\right) = \mathbf{0.3533}$$

where d_2 = 3.895 and d_3 = 0.712 for n = 24.

The x-bar and R charts are shown in Figure 4.15 and Figure 4.16. The hourly data is subgrouped into daily samples of size $n = 24$. Applying the runs rules show that only one point (Sample 10) on the x-bar chart and no points on the R chart are plotting out-of-control. Investigating this point for demonstration purposes only (samples were generated from the in-control simulation) shows that Sample 10's 24 data points include 5 values of 0.6, 5 values of 0.5, 1 value of 0.4, and 4 values of 0.1. With an LCL value of 0.5682, over half of the data points were below this limit. Once again, if this sample had come from an actual network that was not known to be in-control, a search for an assignable cause of the low values would be initiated. The high variability of the individual observed p-path points seems to have been compensated for by averaging the data. Both the data points and the control limits on the x-bar chart are showing less variability than the X chart, and there are no out-of-control points on the R chart which is designed to monitor variance in the data. But as before, when a count-based measure (DwnLnk) is grouped for an x-bar chart, the chart is now representing a different time interval for comparison. Days are compared now instead of hours. Therefore, perhaps over a larger time interval, the high variability of the network with respect to p-path lessens.

Noteworthy is the correspondence between the low value on the x-bar chart for p-path in its Sample 10 and the high value on the x-bar chart for DwnLnk in its Sample 10 (see Figure 4.7). This correspondence conveys the influence of the number of down links on the proportion of paths operating. This makes intuitive sense since a higher number of down links would be expected to lower the proportion of operating paths. Note also though in comparing Figure 4.5 with Figure 4.13, that the same correspondence is not present in the X charts of the individual data points. The relationship between the two measures, DwnLnk and p-path, seems to be more indirect; detectable only in the average of the samples over a longer period of time than in the data points themselves.
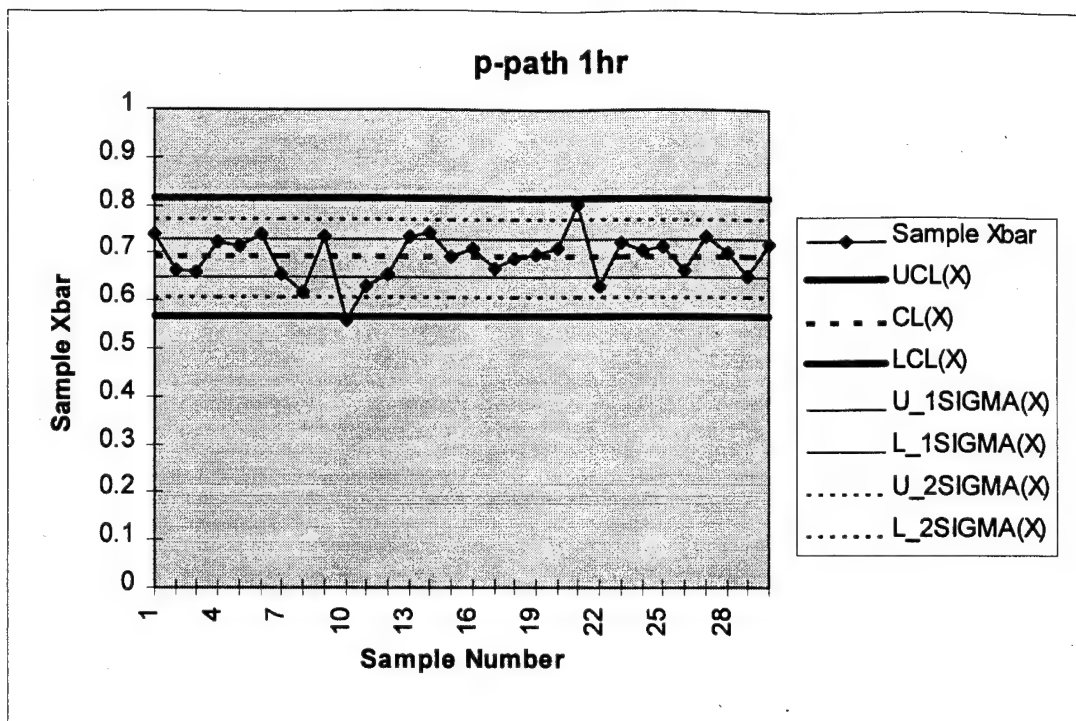
Figure 4.15 x-bar Chart for p-path (1/hr collection rate - daily samples)
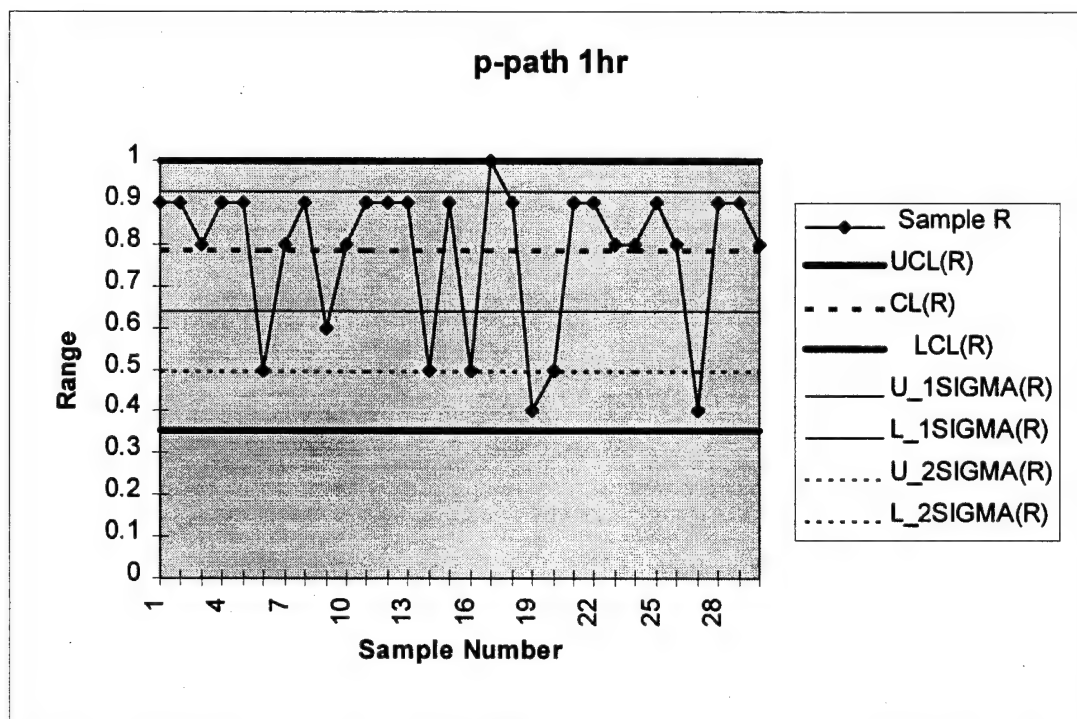
Figure 4.16 R Chart for p-path (1/hr collection rate - daily samples)

Both the XmR charts and the x-bar and R charts seem viable for monitoring p-path. As indicated for DwnLnk, the choice between these two types of charts will be based on the desired rate of detection for out-of-control conditions. Another consideration in this choice is the detection of out-of-control points when aggregating data on the x-bar and R charts that did not appear on the XmR charts. The x-bar and R charts could be more sensitive to shifts in the measure p-path than the XmR charts due to the larger subgrouping (n=24 compared to n=1) of the data (28:157). However, Montgomery states that smaller samples taken more frequently (n=1 every hour) and larger samples taken less frequently (n=24 every 24 hours) are comparable for detecting shifts in the same amount of time (18:111-13). This is true if, using the example sizes given, the earliest a detection is desired is in 1 day. If a shift detection is desired in a few hours, the daily grouping is not satisfactory. So in this case, user preference is the ultimate judge.

4.2.4 Degradation Monitoring.

Once again, degradation will be monitored indirectly through the observation of another performance measure, p-path. The runs rules allow p-path to indirectly measure network degradation by monitoring for decaying conditions, trends, or abrupt shifts just as they did for the overall performance measures in Section 4.1. Assuming that degradation of the network reveals itself as more links failing over time or more failures in a specific link that is contained in more than one path, hence less paths operating over time, a decrease in p-path is an indication of degradation in the network.

4.2.4.1 Degradation Case Study. Now the (s-t) viewpoint will be investigated for detection of link number 13's degradation. The data is plotted on XmR charts for hourly p-path shown in Figure 4.17 and Figure 4.18 . Link 13 is abruptly
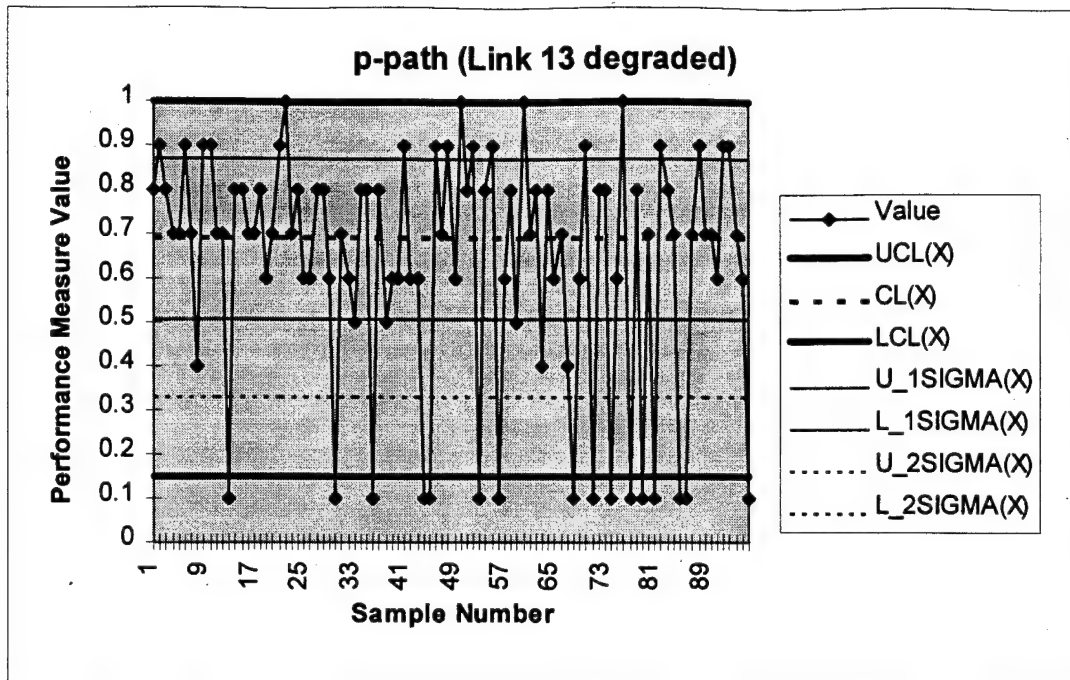
Figure 4.17 X Chart for Hourly p-path (Link 13 degraded)
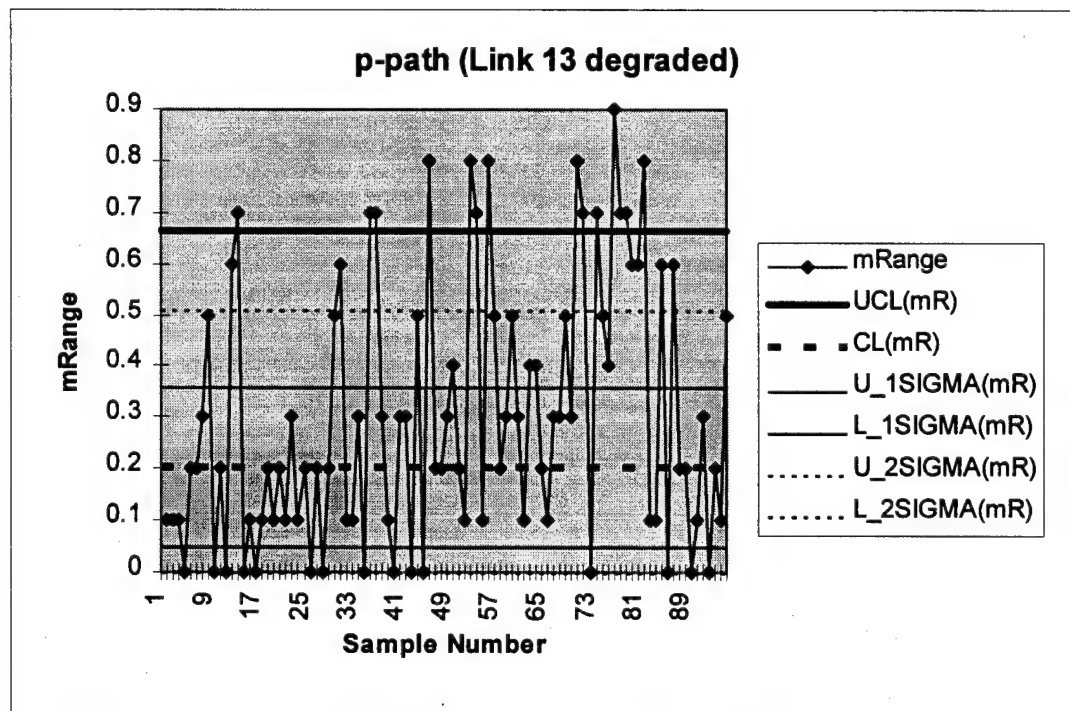
Figure 4.18 mR Chart for Hourly p-path (Link 13 degraded)

4-29

degraded in Sample 25 as before. Looking at the X chart in Figure 4.17, a increase in the amount of out-of-control points can be seen after Sample 25. This measure is inherently variable to begin with, but it seems even more so after the degradation takes place. Even with the wide control limits from the high variability, points are plotting out-of-control more often after Sample 25 than before. Therefore the X chart has detected the degradation. From the mR chart in Figure 4.18, an increase in the variability can also be seen after Sample 25. This is a concurrent indication of some type of degradation. If the assignable cause were not known for this out-of-control indication, a search for one should be initiated. Due to the high variability though, it may not be obvious that the assignable cause began at Sample 25. A search at Sample 31 (the first out-of-control point where the out-of-control points' frequency increases) would probably be chosen as a starting point. Hence, p-path is able to detect the degradation even though the high variability in this measure seems to mask it.

4.3 Individual Link Performance Measures

Many measures were identified as potential indicators of individual link performance. They are link availability (Availability), proportion of times a link is operating when it is checked at regular intervals (p-link), Time to Failure (TTF), Time to Repair (TTR), Time Between Failures (TBF), Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), Mean Time Between Failures (MTBF), and link steady-state availability (SSA). Theoretical considerations of these measures will be discussed, followed by a demonstration of each measure and a discussion of degradation monitoring using these measures.

4.3.1 Theoretical Considerations.

The definition used by the measure Availability is the proportion of time that a link is operating over an interval of time. This is a short-term version of the steady-state availability measure SSA which is defined as the long-run proportion of time that a link is operating. The theoretical value for SSA is computed via:

$$SSA = \frac{MTTF}{MTTF + MTTR} = \frac{12259}{12259 + 754} = 0.942$$

using the theoretical values for MTTF and MTTR assumed for an individual link. MTTR was estimated from summary data provided by the sponsor (MTTR=754 seconds) along with the MTTF over all links (MTTF_overall=169). As mentioned in Section 3.2.3, the steady state equations for the M/M/s queueing model are solved in Appendix D to obtain the individual link MTTF's. Recall from Section 3.2.1 that the MTTF and MTTR distributions are assumed to be iid for all links, in which case the same theoretical SSA value can be used for all links. This value for SSA will be used as the mean (μ) for both Availability and SSA. Their standard deviations (σ), however will be estimated from the data since the theoretical distribution of these availability measures is unknown. The estimated standards are (1 week of hourly data):

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_m}{m} = 0.9404$$

$$\overline{mR} = \sum_{i=1}^{m-1} mR_i = 0.0925$$

The estimated mean x-bar is quite close to the theoretical mean described above (0.9421), hence the estimated mean will be used to show that estimated standards work just as well as the theoretical standards. The corresponding control limits are:

4-31

X chart for hourly Availability:

$$\begin{aligned} \textbf{UCL} &= \bar{x} + 2.66\overline{mR} = 0.9404 + 2.66(0.0925) = 1.1865 \equiv \textbf{1} \\ \textbf{CL} &= \bar{x} = \textbf{0.9404} \\ \textbf{LCL} &= \bar{x} - 2.66\overline{mR} = 0.9404 - 2.66(0.0925) = \textbf{0.6944} \end{aligned}$$

mR chart for hourly Availability:

$$\begin{aligned} \textbf{UCL} &= \overline{mR}D_4 = 0.0925(3.267) = \textbf{0.3022} \\ \textbf{CL} &= \overline{mR} = \textbf{0.0925} \\ \textbf{LCL} &= \overline{mR}D_3 = \textbf{0} \quad \text{always} \end{aligned}$$

The estimated standards for daily Availability are (1 month of daily data):

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_m}{m} = 0.9416$$

$$\overline{mR} = \sum_{i=1}^{m-1} mR_i = 0.0344$$

X chart for daily Availability:

$$\begin{aligned} \textbf{UCL} &= \bar{x} + 2.66\overline{mR} = 0.9416 + 2.66(0.0344) = 1.0331 \equiv \textbf{1} \\ \textbf{CL} &= \bar{x} = \textbf{0.9416} \\ \textbf{LCL} &= \bar{x} - 2.66\overline{mR} = 0.9416 - 2.66(0.0344) = \textbf{0.8501} \end{aligned}$$

mR chart for daily Availability:

$$UCL = \overline{mR}D_4 = 0.0344(3.267) = \mathbf{0.1124}$$

$$\mathbf{CL} = \overline{mR} = \mathbf{0.0344}$$

$$\mathbf{LCL} = \overline{mR}D_3 = \mathbf{0} \quad \text{always}$$

The estimated standards for hourly Availability grouped into daily samples are (1 week of hourly data):

$$\overline{\overline{x}} = \frac{\overline{x}_1 + \overline{x}_2 + \cdots + \overline{x}_m}{m} = 0.9397$$

$$\overline{R} = \frac{R_1 + R_2 + \cdots + R_m}{m} = 0.3615$$

The control limits for the x-bar chart are:

$$UCL = \overline{\overline{x}} + A_2\overline{R} = 0.6914 + 0.157(0.7833) = \mathbf{0.8145}$$

$$\mathbf{CL} = \overline{\overline{x}} = \mathbf{0.6914}$$

$$\mathbf{LCL} = \overline{\overline{x}} - A_2\overline{R} = 0.6914 - 0.157(0.7833) = \mathbf{0.5682}$$

where A2 = 0.157 for n = 24.

4-33

The control limits for the R chart are:

$$\mathbf{UCL} = \overline{R} + 3d_3 \frac{\overline{R}}{d_2} = 0.7833 + 3(0.712)\left(\frac{0.7833}{3.895}\right) = 1.2129 \equiv$$

$$\mathbf{CL} = \overline{R} = \mathbf{0.7833}$$

$$\mathbf{LCL} = \overline{R} - 3d_3 \frac{\overline{R}}{d_2} = 0.7833 - 3(0.712)\left(\frac{0.7833}{3.895}\right) = \mathbf{0.3533}$$

where $d_2 = 3.895$ and $d_3 = 0.712$ for $n = 24$.

The proportion p-link is another measure based on a binomial count. This measure, p-link, is similar to the measure p-up since it is also checking for operating links at 300 second time intervals. In contrast though, a check is made of a link's status every 300 seconds and then these checks are aggregated to produce a count over an hourly and a daily interval. (P-up has a sample size of 77 since it checks *all* links every 300 seconds instead of just one link). The hourly interval contains 12 checks per sample and the daily interval contains 288 checks per sample. The data is being grouped since only one link is being checked. If each of these checks were plotted individually, all that would be plotted would be ones (link is up) or zeroes (link is down). Hence, the data must be grouped, so hourly and daily samples seem to be a natural grouping. Similar to the earlier proportion measures p-up and p-down, the value of p has remained the same (p = 4.46/77) since it still represents the probability that, but the value of n has changed (n = 12 hourly, n = 288 daily) for this binomial distribution.. The binomial model can be used for this proportion, p-link, since each link's subsequent failures are independent of each other just as each link's subsequent times-to-failure are independent of each other. Hence the probability that a link is down at some arbitrary point in time, p, is the same at each

4-34

check of the link. Therefore, the mean (μ) and standard deviation (σ) for p-link are defined and are used to compute the following control limits:

p chart for hourly p-link:

$$\text{UCL} = (1-\bar{p})+3\sqrt{\frac{(1-\bar{p})\bar{p}}{n}} = 1-\frac{4.46}{77}+3\sqrt{\frac{\left(1-\frac{4.46}{77}\right)\left(\frac{4.46}{77}\right)}{12}} = 1.1444 \equiv 1$$

$$\text{CL} = 1-\bar{p} = 1-\frac{4.46}{77} = 0.9421$$

$$\text{LCL} = (1-\bar{p})-3\sqrt{\frac{(1-\bar{p})\bar{p}}{n}} = 1-\frac{4.46}{77}-3\sqrt{\frac{\left(1-\frac{4.46}{77}\right)\left(\frac{4.46}{77}\right)}{12}} = 0.7398$$

p chart for daily p-link:

$$\text{UCL} = (1-\bar{p})+3\sqrt{\frac{(1-\bar{p})\bar{p}}{n}} = 1-\frac{4.46}{77}+3\sqrt{\frac{\left(1-\frac{4.46}{77}\right)\left(\frac{4.46}{77}\right)}{288}} = 0.9834$$

$$\text{CL} = 1-\bar{p} = 1-\frac{4.46}{77} = 0.9421$$

$$\text{LCL} = (1-\bar{p})-3\sqrt{\frac{(1-\bar{p})\bar{p}}{n}} = 1-\frac{4.46}{77}-3\sqrt{\frac{\left(1-\frac{4.46}{77}\right)\left(\frac{4.46}{77}\right)}{288}} = 0.9008$$

Hence, with these standards known for p-link (for the case study network model), they do not need to be estimated from the sample data.

TTF, TTR, and TBF all come from known distributions (exponential) with standards provided by the sponsor as mentioned earlier in this section. The sample MTTF, MTTR, and MTBF, since they are an average of their respective failure/repair times, can then infer their standards from those of their respective failure/repair times.

These theoretical means of the exponential distributions of the sample MTTF and sample MTTR were programmed into the simulation model and can therefore be used as theoretical values for the control charts. The individual link TBF (and sample MTBF) is calculated as the sum of TTF (sample MTTF) and TTR (sample MTTR). These values for MTTF, MTTR, and MTBF are used as the means of their respective charts as well as the means for their corresponding individual value charts (TTF, TTR, and TBF). Also, since the distributions for the measures TTF, TTR, and TBF are assumed to be exponential, the standard deviations for these measure are equal to their respective means while the standard deviations for the measures MTTF, MTTR, and MTBF are equal to their respective means divided by m = the number of individual times used in the average. These values are:

$$\mu_{MTTF} = \mu_{TTF} = 12259 \qquad \mu_{MTTR} = \mu_{TTR} = 754 \qquad \mu_{MTBF} = \mu_{TBF} = 13013$$
$$\sigma_{TTF} = 12259 \qquad\qquad \sigma_{TTR} = 754 \qquad\qquad \sigma_{TBF} = 13013$$
$$\sigma_{MTTF} = 12259/m \qquad \sigma_{MTTR} = 754/m \qquad \sigma_{MTBF} = 13013/m$$

Thus, the standards for all six of these performance measures' distributions are known when m is determined (for the case study network model) and do not need to be estimated from the sample data. The corresponding control limits for TTF, TTR, and TBF are calculated below:

X chart for TTF:

$$\mathbf{UCL} = \mu + 3\left(\frac{\overline{mR}}{d_2}\right) = 12259 + 3(12259) = \mathbf{49036}$$
$$\mathbf{CL} = \mu = \mathbf{12259}$$
$$\mathbf{LCL} = \mu - 3\left(\frac{\overline{mR}}{d_2}\right) = 12259 - 3(12259) = -24518 \equiv \mathbf{0}$$

where for n = 2:

$$\overline{mR} = \sigma d_2$$
$$d_2 = 1.128$$

mR chart for TTF:

$$\mathbf{UCL} = \overline{mR}D_4 = 12259(1.128)(3.267) = \mathbf{45176.6}$$
$$\mathbf{CL} = \overline{mR} = \mathbf{13828.2}$$
$$\mathbf{LCL} = \overline{mR}D_3 = \mathbf{0} \quad \text{always (usually not annotated on chart)}$$

where for n = 2:

$$D_3 = 0$$
$$D_4 = 3.267$$

X chart for TTR:

$$\mathbf{UCL} = \mu + 3\left(\frac{\overline{mR}}{d_2}\right) = 754 + 3(754) = \mathbf{3016}$$
$$\mathbf{CL} = \mu = \mathbf{754}$$
$$\mathbf{LCL} = \mu - 3\left(\frac{\overline{mR}}{d_2}\right) = 754 - 3(754) = -1508 \equiv \mathbf{0}$$

mR chart for TTR:

$$\mathbf{UCL} = \overline{mR}D_4 = 754(1.128)(3.267) = \mathbf{2778.6}$$
$$\mathbf{CL} = \overline{mR} = \mathbf{850.5}$$
$$\mathbf{LCL} = \overline{mR}D_3 = \mathbf{0} \quad \text{always (usually not annotated on chart)}$$

X chart for TBF:

$$\mathbf{UCL} = \mu + 3\left(\frac{\overline{mR}}{d_2}\right) = 13013 + 3(13013) = \mathbf{52052}$$
$$\mathbf{CL} = \mu = \mathbf{13013}$$
$$\mathbf{LCL} = \mu - 3\left(\frac{\overline{mR}}{d_2}\right) = 13013 - 3(13013) = -26026 \equiv \mathbf{0}$$

mR chart for TBF:

$$UCL = \overline{mR}D_4 = 13013(1.128)(3.267) = 47955.2$$
$$CL = \overline{mR} = 14678.6$$
$$LCL = \overline{mR}D_3 = 0 \quad \text{always (usually not annotated on chart)}$$

4.3.2 Autocorrelation of Data Points.

All autocorrelation computations are calculated using data from Link #1 for demonstration purposes. The measure p-link is the only measure in this section collected every 300 seconds, but it is then aggregated to produce a count over an hourly and a daily interval. Thus, the data points collected once every hour and once every day are investigated to ensure no auto-correlation. The resulting autocorrelation at lag 1 and its 95% standard error limits are shown in Table 4.3 for one month of data.

Table 4.3 Autocorrelation for p-link

Collection Rate	r_1	Limits	Sample Size	Autocorrelation
1/hour	0.023	$-0.073 \leq r_1 \leq 0.073$	720	no significant
1/day	0.246	$-0.358 \leq r_1 \leq 0.358$	30	no significant

Link Availability is checked next for autocorrelation. This measure is computed over an interval of one hour and also one day. The results are shown in Table 4.4.

Table 4.4 Autocorrelation of Availability

Collection Rate	r_1	Limits	Sample Size	Autocorrelation
1/hour	0.109	$-0.073 \leq r_1 \leq 0.073$	720	slight
1/day	-0.110	$-0.358 \leq r_1 \leq 0.358$	30	no significant

4-38

The next measures checked are TTF, TTR, TBF, and sample MTTF, MTTR, and MTBF. These measures are all collected after each failure and repair of a link occur. Since the link failures are assumed to be independent in Chapter 1, TTF, TTR, and TBF should not be autocorrelated. Their autocorrelations at lag 1 agree with this assumption with values -0.011, -0.049, and -0.011 respectively. In contrast, if the sample MTTF, MTTR, and MTBF are cumulative averages of all past TTFs, TTRs, and TBFs respectively, then the sample MTTF, MTTR, and MTBF are all expected to be correlated. In addition, they are all expected to converge to their respective theoretical means. Their corresponding autocorrelations at lag 1 are indeed high at 0.880, 0.609, and 0.875. This autocorrelation can easily be seen in an time series plot chart for the cumulative sample MTTF of Link #1 shown in Figure 4.19.
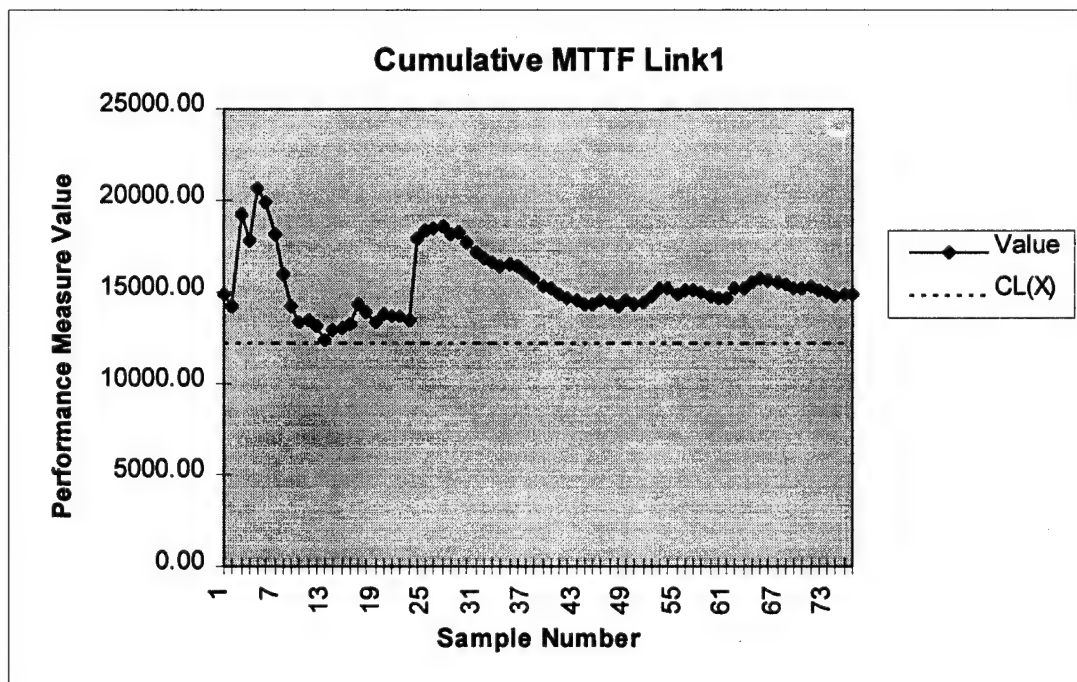
Figure 4.19 Time Series Plot of Cumulative MTTF Link #1

As indicated earlier in Section 4.1.2, autocorrelated data cannot be used on the standard control charts being investigated in this study. Therefore, the measures sample MTTF, MTTR, and MTBF should not be cumulative. Instead they should be calculated over a specified time period. The choice of what this time period should be can be based on the theoretical mean of the measure. The time interval should be large enough so as to allow enough failures to occur for an accurate calculation. The individual link failure rate for the case study network is 1 failure/12259 seconds (or 1 failure/3.4 hours). Therefore, an hourly collection rate would not be appropriate. A daily collection rate would be much better and is investigated here for autocorrelation using Link #1's daily MTTF as an example. A time series plot of Link #1's daily MTTF is shown in Figure 4.20. This plot does not seem to be showing significant autocorrelation (confirmed by an autocorrelation at lag 1 value of -0.338 using a sample size of 30), but it is definitely converging toward its theoretical mean. With this kind of convergence in these measures (MTTF, MTBF, and MTTR), charting them does not seem to provide any useful information. Their corresponding individual measurements TTF, TBF and TTR are still viable though and will be used to monitor the network.
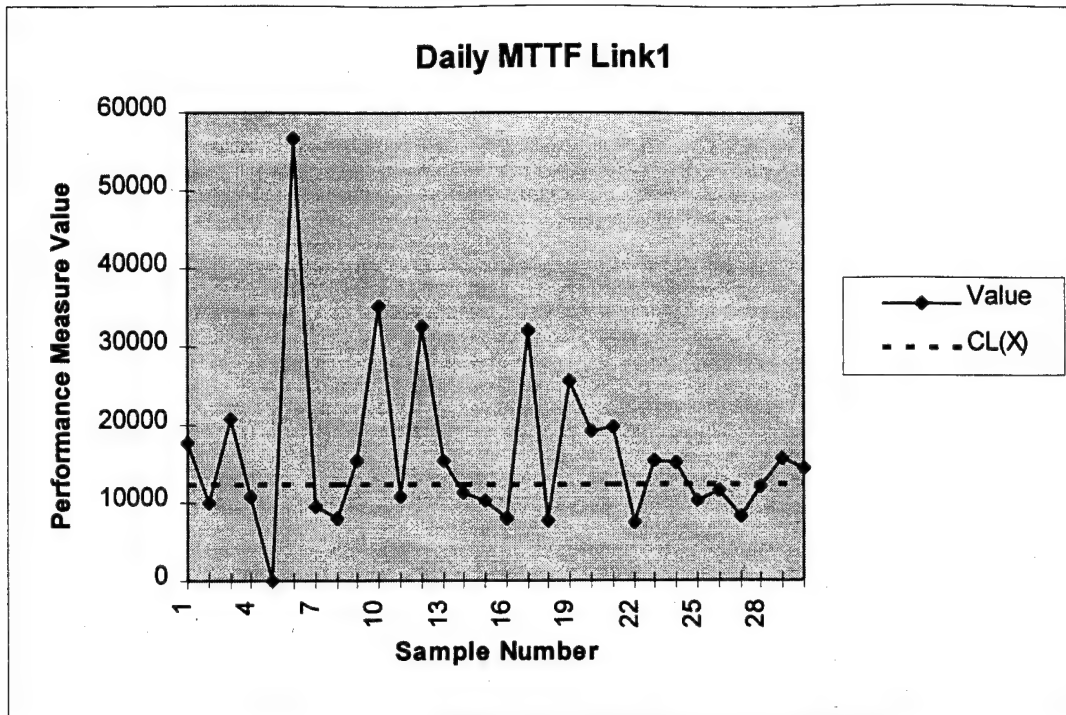
Figure 4.20 Time Series Plot of Daily MTTF Link #1

A direct consequence of the convergence of MTTF and MTTR data is that the SSA data will also converge (as it should since it is a steady-state measure) since it is computed directly from these two previous measures. It is also autocorrelated as shown by an autocorrelation at lag 1 value of 0.587. A time series plot of the SSA data also shows this autocorrelation and a convergence toward 1 as the time interval increases. The time series plot is shown in Figure 4.21.
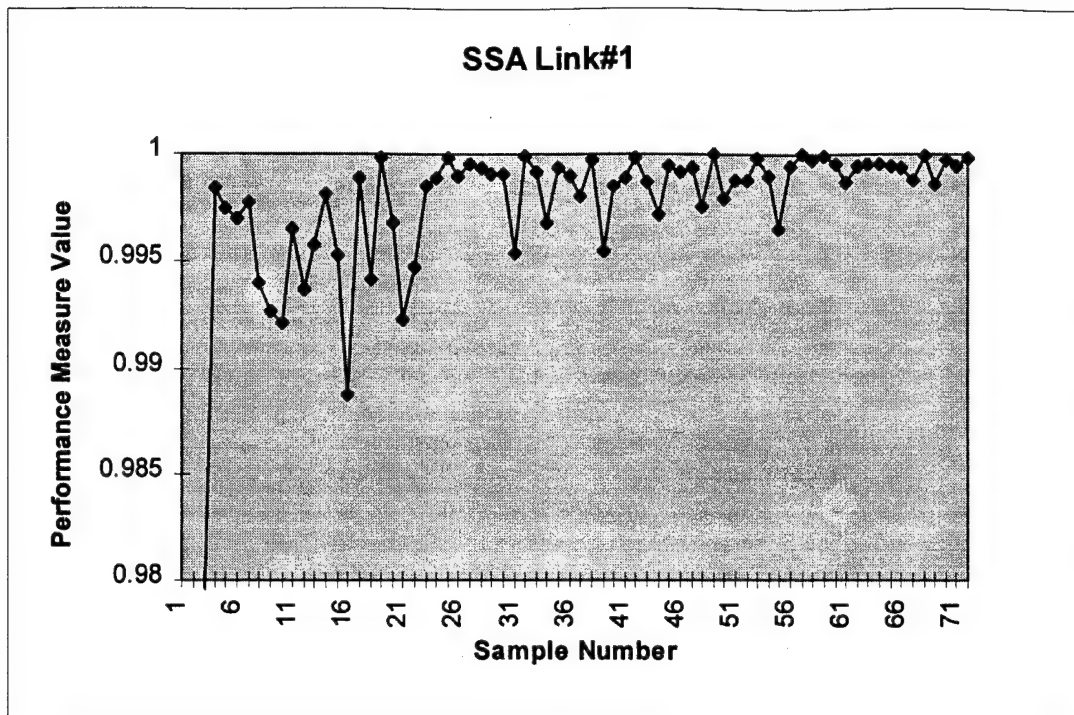
Figure 4.21 Time Series Plot for SSA Link #1 (Steady State Availability)

4.3.3 Demonstration of Procedures.

The charts identified in Chapter 3 for monitoring the remaining performance measures will be demonstrated here. Each chart in this section is shown with its control limits (UCL, CL, and LCL) and 1-sigma and 2-sigma warning limits. All limits in this section are computed using the respective theoretical and estimated standards described in Section 4.3.1.

4.3.3.1 Link Availability. The measure **Availability** has two possible control charting techniques; XmR charts and x-bar and R charts. This measure is computed over both a 1 hour interval and a 1 day interval. The hourly XmR charts are shown in Figure 4.22 and Figure 4.23 and the daily XmR charts are shown in Figure 4.36 and Figure 4.37.

4-42
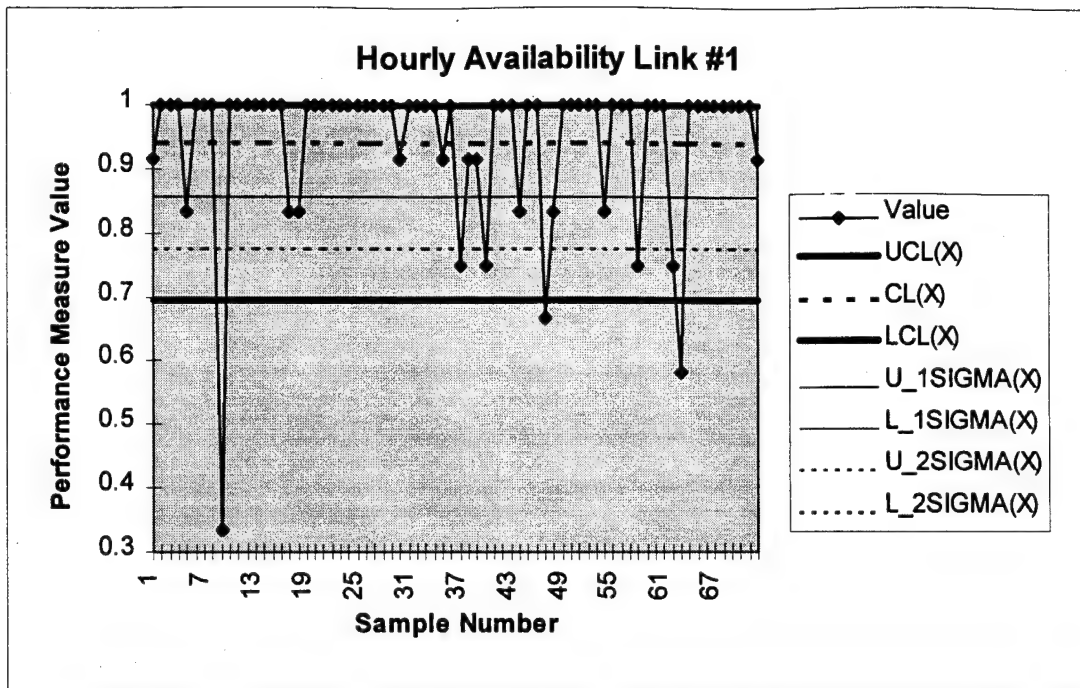
Figure 4.22 X Chart for Availability (computed & collected hourly)
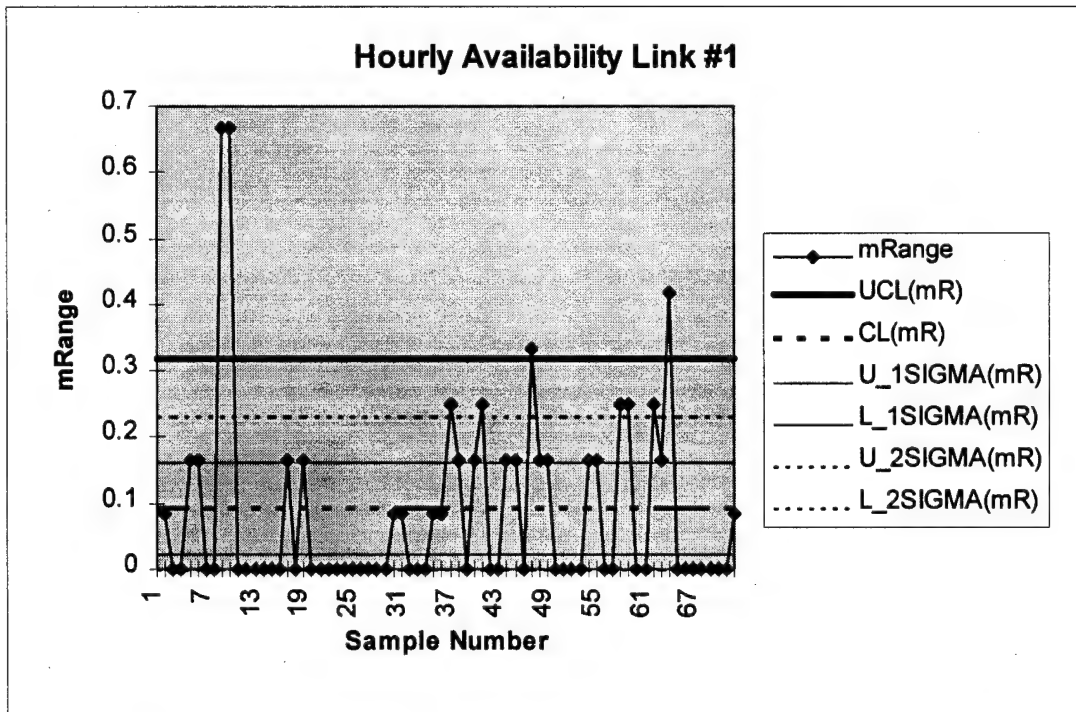
Figure 4.23 mR Chart for Availability (computed & collected hourly)
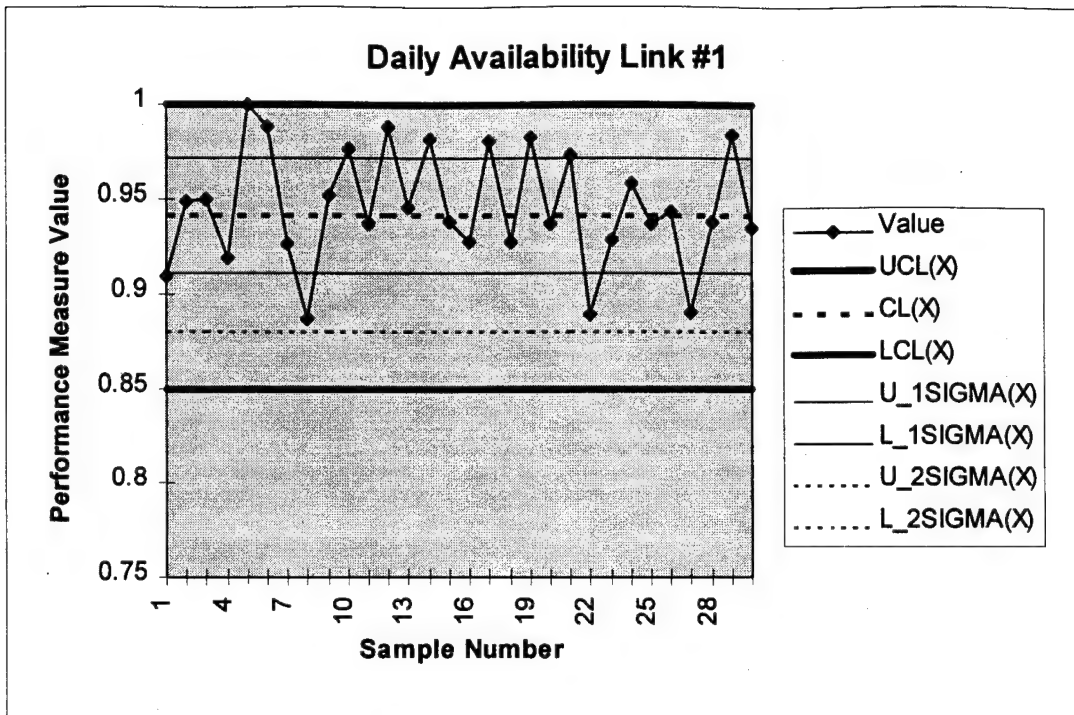
Figure 4.24 X Chart for Availability (computer & collected daily)
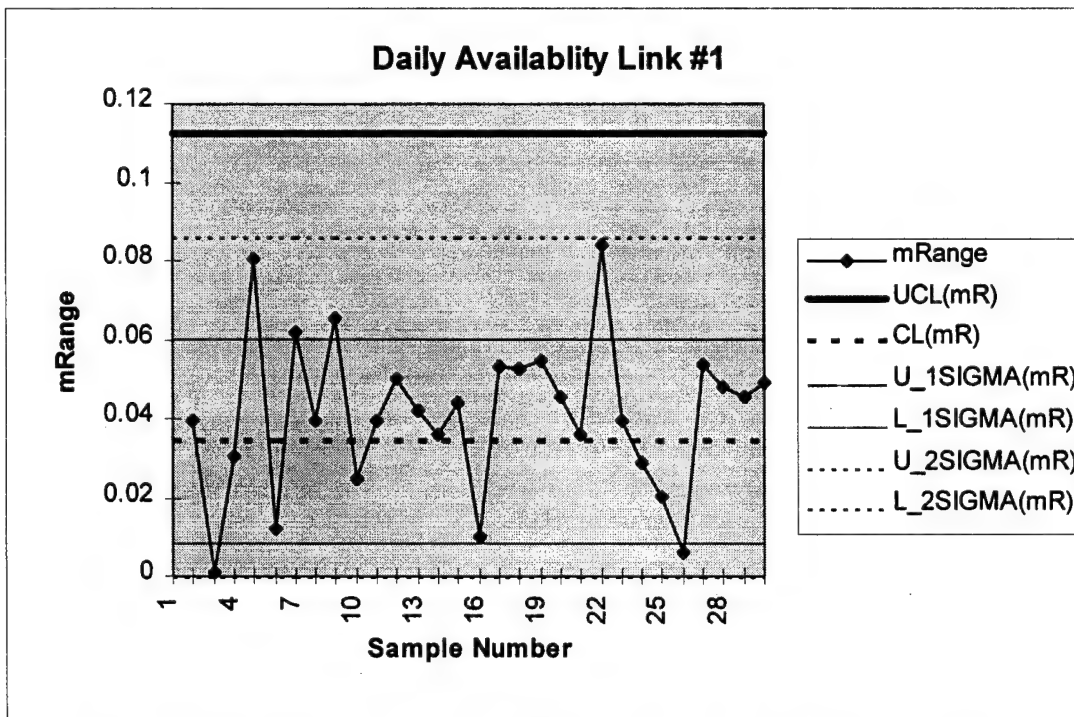
Figure 4.25 mR Chart for Availability (computed & collected daily)

Applying the runs rules show that many points are plotting out-of- control on both hourly charts in Figure 4.22 and Figure 4.23 (the runs at values 1 and 0 are painfully obvious). Since it is known that there are no assignable causes, something else must be causing these out-of-control points. The cause is the failure rate of an individual link (1 failure/3.4 hours) compared to the collection rate (1/hour). Not enough failures are occurring in an hour's time to compute an accurate value of Availability. Hence, there are many values of 1 plotted on the UCL of the X chart which, in turn, cause the many values of 0 plotted on the LCL of the mR chart. Looking now at the daily charts in Figure 4.36 and Figure 4.37, no points are plotting out-of-control indicating an in-control network as it should. As a result, Availability should be computed over an interval of at least one day with the current individual link failure rate.

The x-bar and R charts are shown in Figure 4.26 and Figure 4.27. The hourly data are subgrouped into daily samples of size n = 24. Applying the runs rules to these two charts show that *several* points on both charts are plotting out-of-control. Some of these out-of-control points are clearly outside the control limits on the x-bar chart in Figure 4.26 (i.e., samples 2, 5, 6, 8, 12, 17, 18, 21, 28, and 29), while still other sample points are classified as out-of-control due to a run containing them (i.e., in Figure 4.26, Samples 28 and 29 are a 2-of-3 run and, in Figure 4.27, Samples 12, 13, and 14 are a 3-of-3 run and Samples 20, 21, 22, and 24 are a 4-of-5 run). Remembering the previous finding from the XmR charts for hourly Availability in Figure 4.22 and Figure 4.23, that Availability should be computed over an interval of at least one day with the current individual link failure rate, the daily aggregation of hourly calculations is not appropriate. A weekly or monthly grouping of daily availability would be more worthwhile.
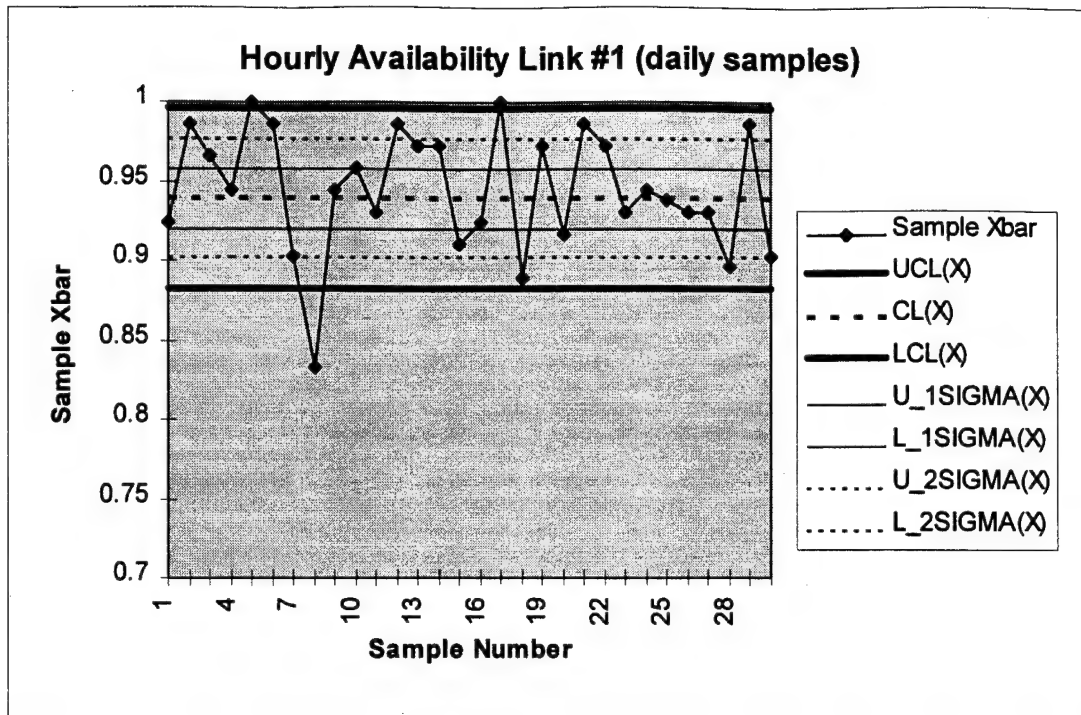
Figure 4.26 x-bar Chart for Availability (computed/collected hourly -daily samples)
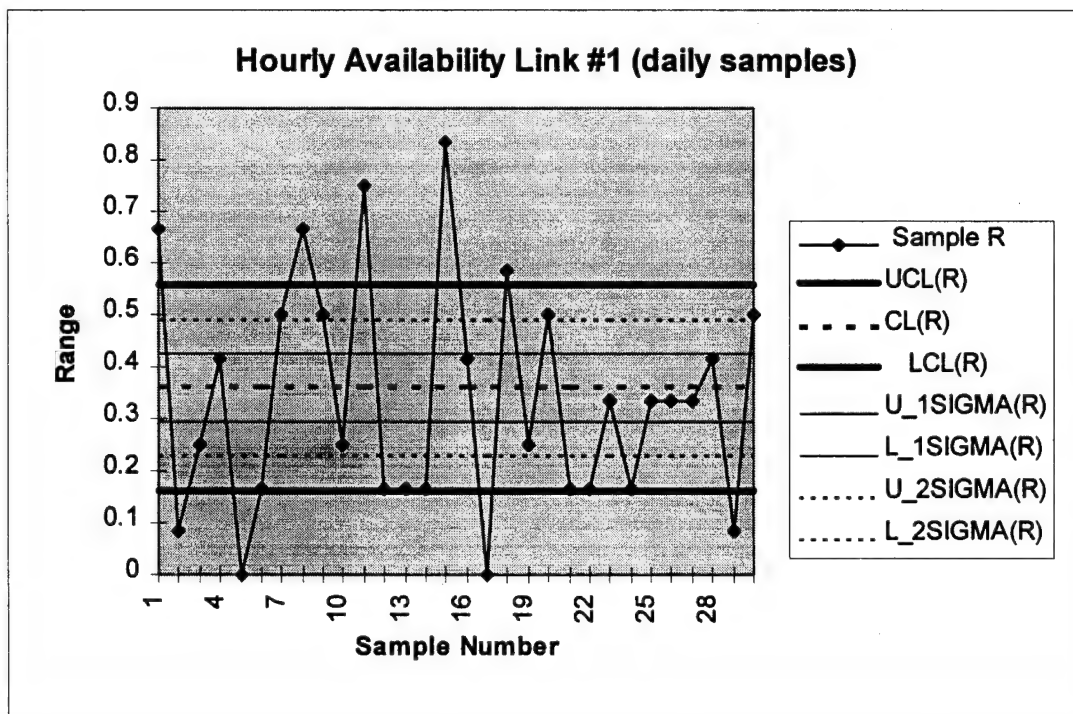
Figure 4.27 R Chart for Availability (computed/collected hourly - daily samples)

4.3.3.2 Proportion of Link Up-checks. The measure **p-link** has one possible control charting technique; the p chart. This measure is computed over both a 1 hour interval and a 1 day interval. The hourly p chart is shown in Figure 4.28 and the daily p chart is shown in Figure 4.29. Applying the runs rules show that many points are plotting out-of-control on the hourly chart. Once again, this is due to the fact that the failure rate of an individual link (1failure/3.4 hours) is much larger that the collection rate here (1/300 seconds). Not enough failures are occurring every 300 seconds to compute an accurate value of this proportion, p-link. Too many values of 1 are being computed. As with Availability, the data should be collected on a less frequent basis, and the proportion should be computed over an interval of one day with the current individual link failure rate. Looking now at the daily chart, in Figure 4.29, there are still several out-of-control points and two 'runs' above the 2-sigma limit. The same problem still exists as for Availability; not enough failures are occurring every 300 seconds. Computing the proportion over an day's interval rather than a hour's interval will not fix this problem. The every 300 second data is still being used. If a larger time interval were used for data collection, then the p chart would be well suited to monitor the performance measure p-link since this measure fits the conditions for the binomial probability model in Section 3.1.3.
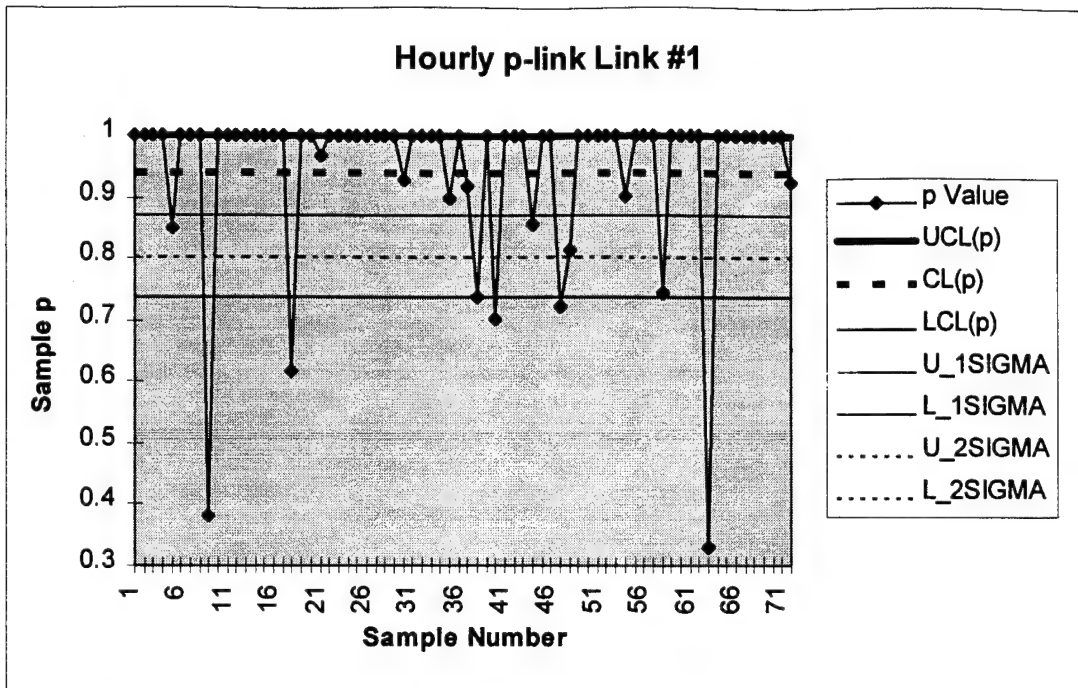
Figure 4.28 p Chart for p-link (collected 1/300sec - computed hourly)
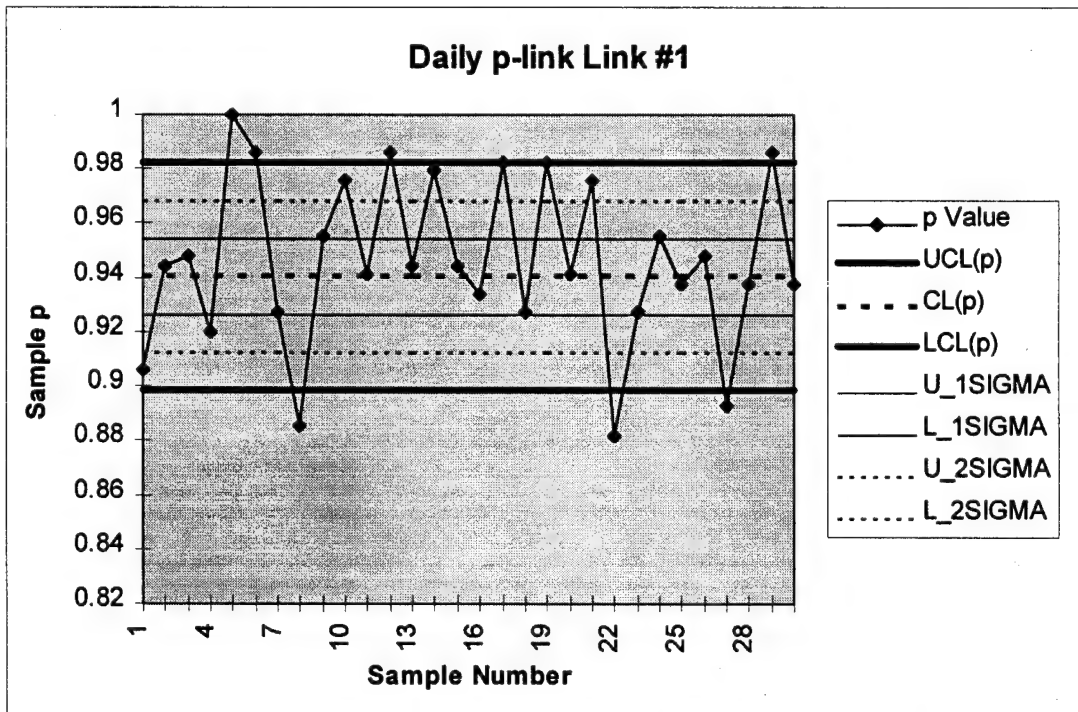
Figure 4.29 p Chart for p-link (collected 1/300sec - computed daily)

4.3.3.3 Time to Failure/Time to Repair/Time Between Failures. The measures **TTF**, **TTR**, and **TBF** have one possible control charting technique; XmR charts. The XmR charts for TTF are shown in Figure 4.30 and Figure 4.31, the XmR charts for TTR are shown in Figure 4.32 and Figure 4.33, and the XmR charts for TBF are shown in Figure 4.34 and Figure 4.35. Applying the runs rules show that only one point is plotting out-of-control (Sample 24 - the 24th failure) on both the X chart for TTF and the X chart for TBF. Since TBF is the sum of TTF and TTR, a correspondence between TTF and TBF is expected. This single out-of-control point is due to a chance occurrence of the draw from the exponential distributions included in the simulation since the network is known to be in control.

The monitoring of these three performance measures will complement each other well. An out-of-control point on a TBF chart should be accompanied by an out-of-control point on either the TTF or TTR charts. Care must be taken though since the TTF may dominate over the TTR if its mean value is significantly larger than TTR's (as in this case study). However, an out-of-control point on the TBF chart with a corresponding out-of-control point on the TTF chart should not substantiate automatically disregarding the TTR chart. Both TTF and TTR may be contributing. Since an out-of-control point on the TBF charts should be cross checked with both the TTF charts and the TTR charts to determine which is contributing to the out-of-control condition, the TBF charts are like an aggregate of the measures TTF and TTR. If only one measure is desired to be monitored, the TBF should be monitored to detect shifts from both TTF and TTR. But if two measures can be monitored, TTF and TTR are sufficient without the additional charting of TBF. These measures will be particularly useful in helping to identify the cause of degradation discussed in the next section.

4-49
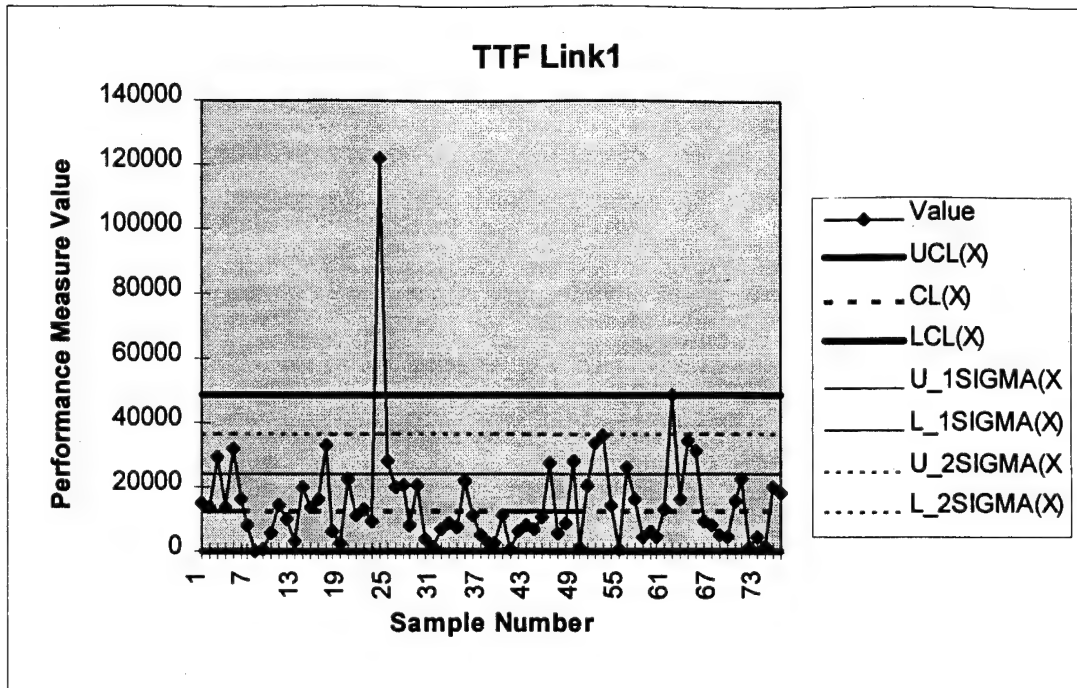
Figure 4.30 X chart for TTF Link #1
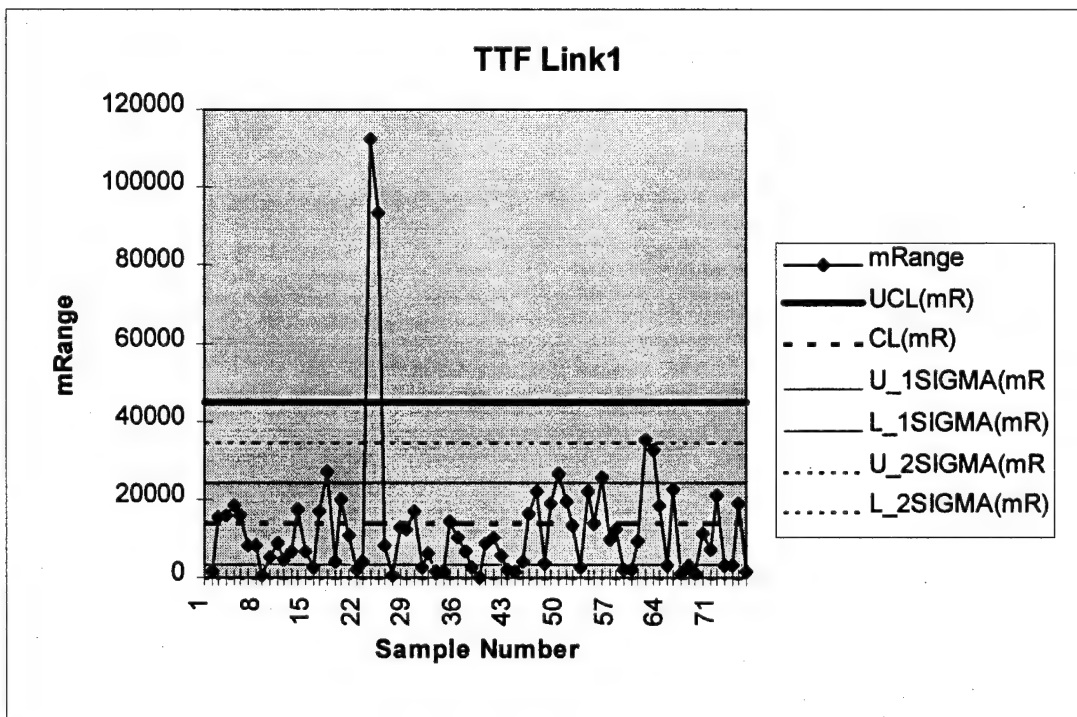
Figure 4.31 mR Chart for TTF Link #1
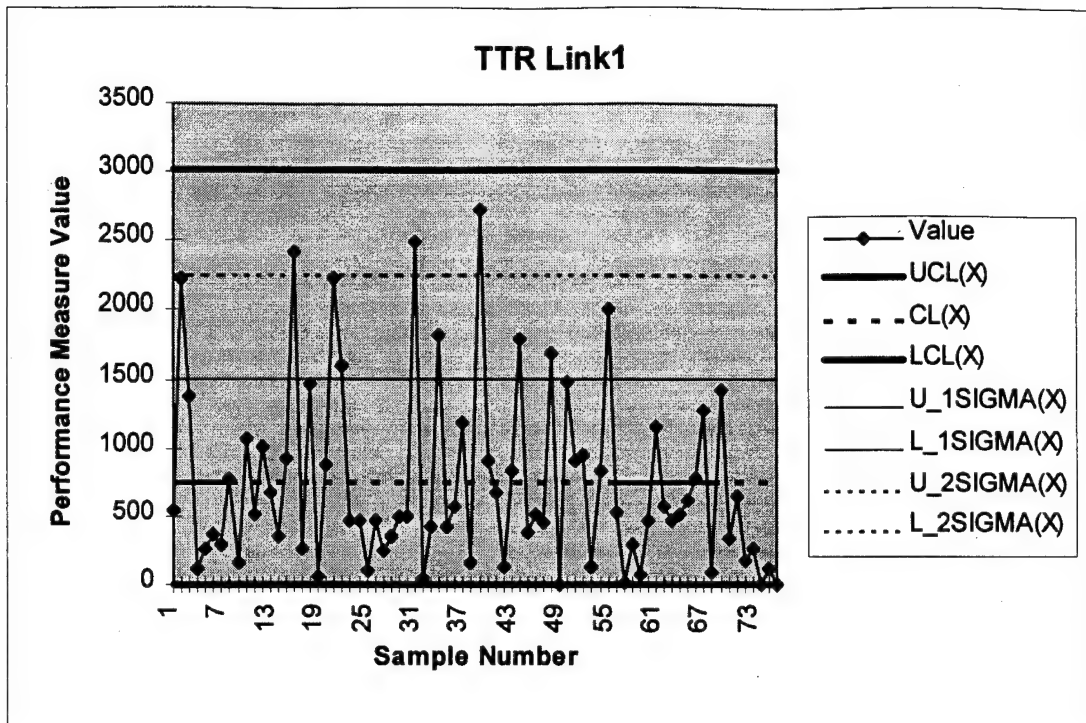
Figure 4.32 X Chart for TTR Link #1
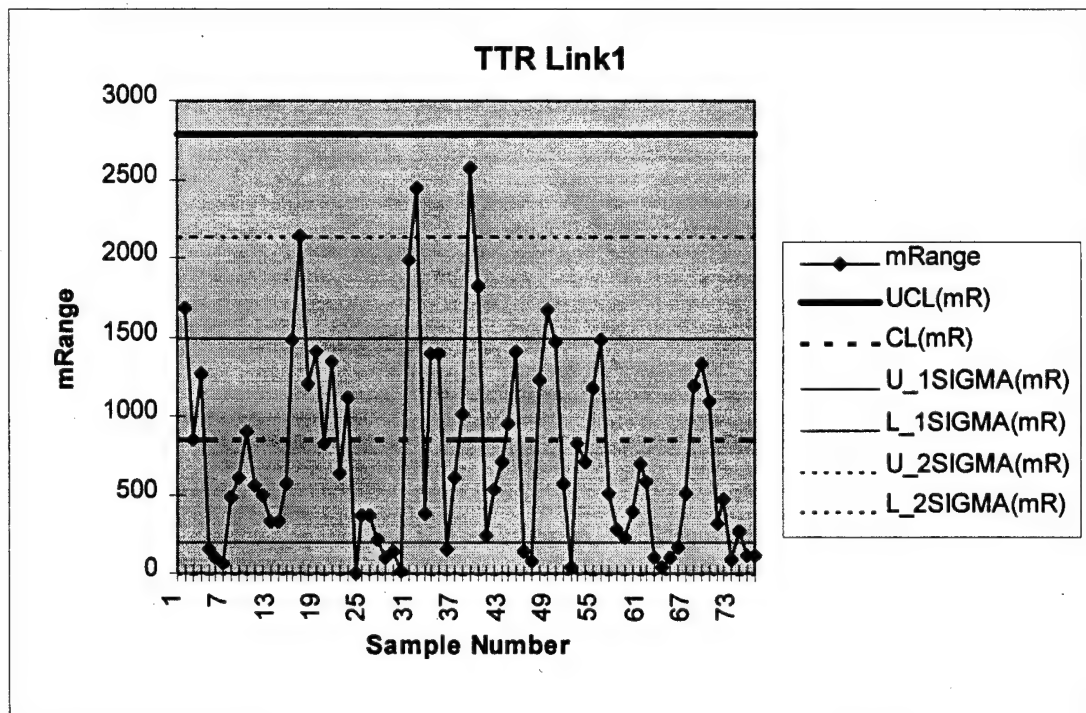
Figure 4.33 mR Chart for TTR Link #1

4-51
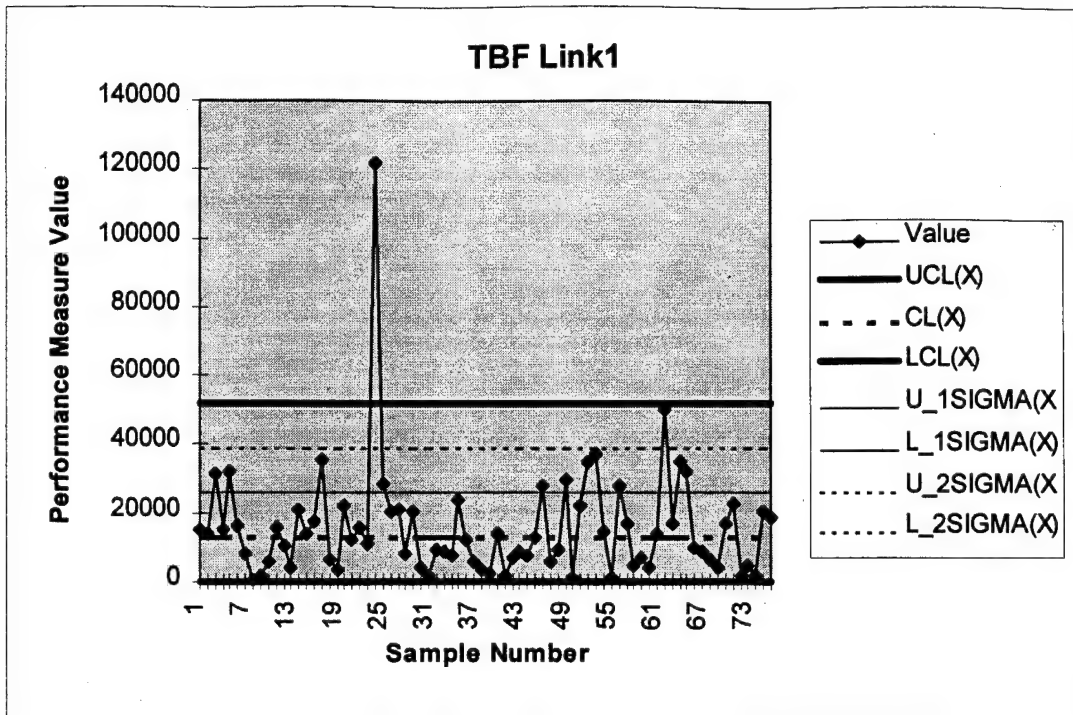
Figure 4.34 X Chart for TBF Link #1
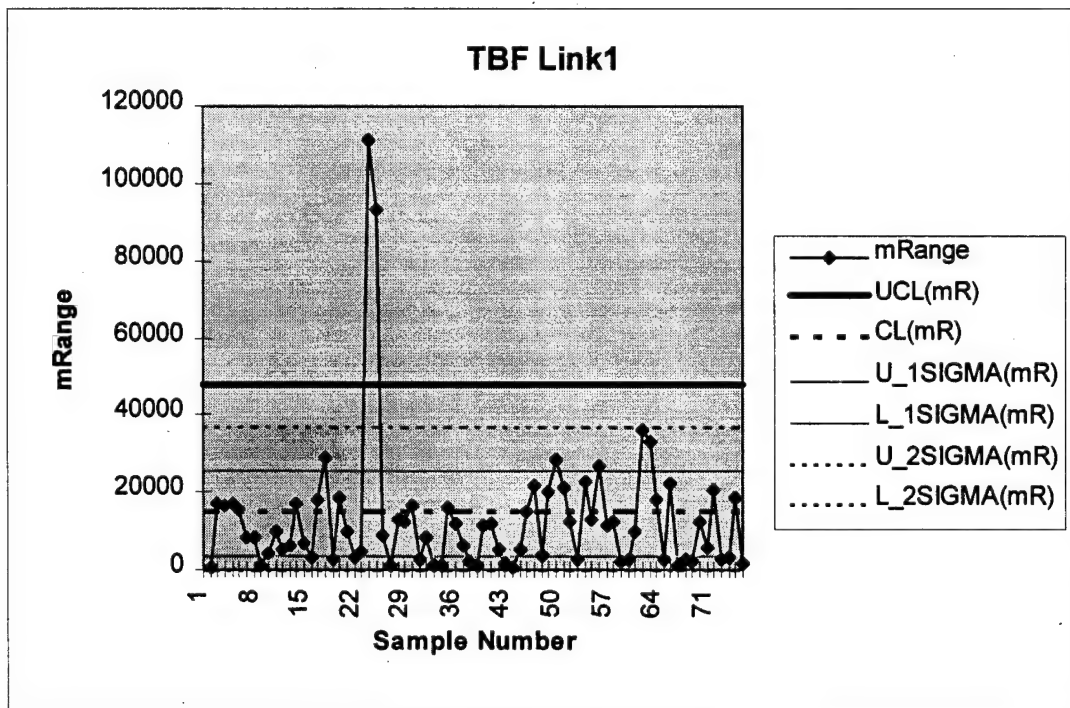
Figure 4.35 mR Chart for TBF Link #1

One additional concern with these measures is that TTF and TTR are known to have exponential distributions. Even though data from any distribution can be plotted on control charts, knowing the data's underlying distribution will indicate the behavior of the data on the control chart. Control charts are designed with the normal distribution in mind, and hence the control limits are computed for normally distributed data. Comparing the exponential distribution's relationship to the control limits to the normal distribution's relation ship shows a moderate difference in relation to the center line and the 1-sigma limits. For the exponential distribution, approximately 62 % of the points should plot below the center line as compared to 50 % of the points for the normal distribution. Also for the exponential distribution, 98.2 % of the points should plot within the 3-sigma limits as compared to 97.7 % for the normal distribution (28:60-4). Hence, knowing the distribution of the data could help in identifying a pattern due to the underlying distribution instead of an assignable cause as might be indicated by the runs rules. This knowledge of the distribution could thus prevent a false alarm of an out-of-control condition.

4.3.4 Degradation Monitoring.

Once again, network degradation will be monitored indirectly through the observation of other performance measures, and the runs rules allow this indirect monitoring by detecting decaying conditions or trends just as they did for the overall performance measures and (s-t) performance measure. Assuming that degradation of the network reveals itself as more links failing over time, shorter TTFs and/or longer TTRs over time, trends can be monitored with the performance measures p-link, Availability, TTF, TTR, and TBF. A slow decrease of p-link is an indication of degradation in the network due to the first assumption that more links are failing over time in a degrading network. Availability will be affected by a change in TTF. Shorter TTFs (less uptime)

4-53

will cause a decrease in Availability. Finally, by monitoring all three TTF, TTR, and TBF charts for any trends (runs), location of the cause will be facilitated. A combination of TBF decreases and TTR increases point to example problems with either the repair facilities or the magnitude of the link's failure. A combination of TBF decreases and TTF decreases point to example problems such as high network loading, low quality of repairs, equipment wearing out. These indications from all three measures could be any combination of these example problems mentioned. Degradation can be easily detected in this manner.

      4.3.4.1 Degradation Case Study. Now the degradation of Link 13 will be monitored through individual link performance measures. First, the daily Availability of Link 13 is plotted on XmR charts and shown in Figure 4.36 and Figure 4.37. The degradation occurred in Sample 16 for this demonstration (a daily measure is now being used as compared to an hourly measure for p-down and p-path). Looking at the X chart in Figure 4.36, the abrupt decrease in the link's availability is easily seen in Sample 16. These is also a corresponding out-of-control indication on the mR chart in Figure 4.37. If the change were not so abrupt though, runs rules would be used to indicate an out-of-control condition. Next, the TTF's for Link 13 are plotted on the XmR charts shown in Figure 4.38 and Figure 4.39. The degradation occurred after Sample 30 (the 30th failure - this measure's samples are for each failure, not a set interval). The X chart in Figure 4.38 clearly shows the abrupt decrease in Link 13's TTF after Sample 30. The mR chart in Figure 4.39 corresponds to this abrupt shift as it should. As stated earlier, if the shift were not so abrupt, a gradual decrease in TTF would be seen and the runs rules would help to detect the degradation. Both the measures of Availability and TTF for Link 13 easily detected the degradation of Link 13.
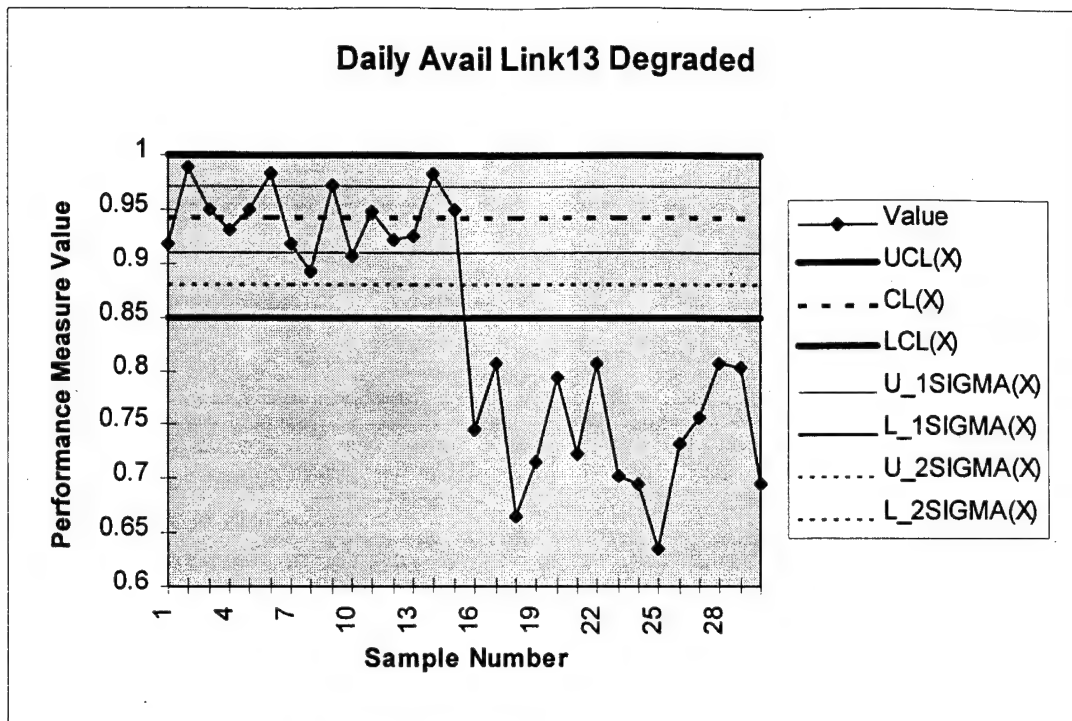
Figure 4.36 X Chart for Daily Availability Link 13 (degraded)
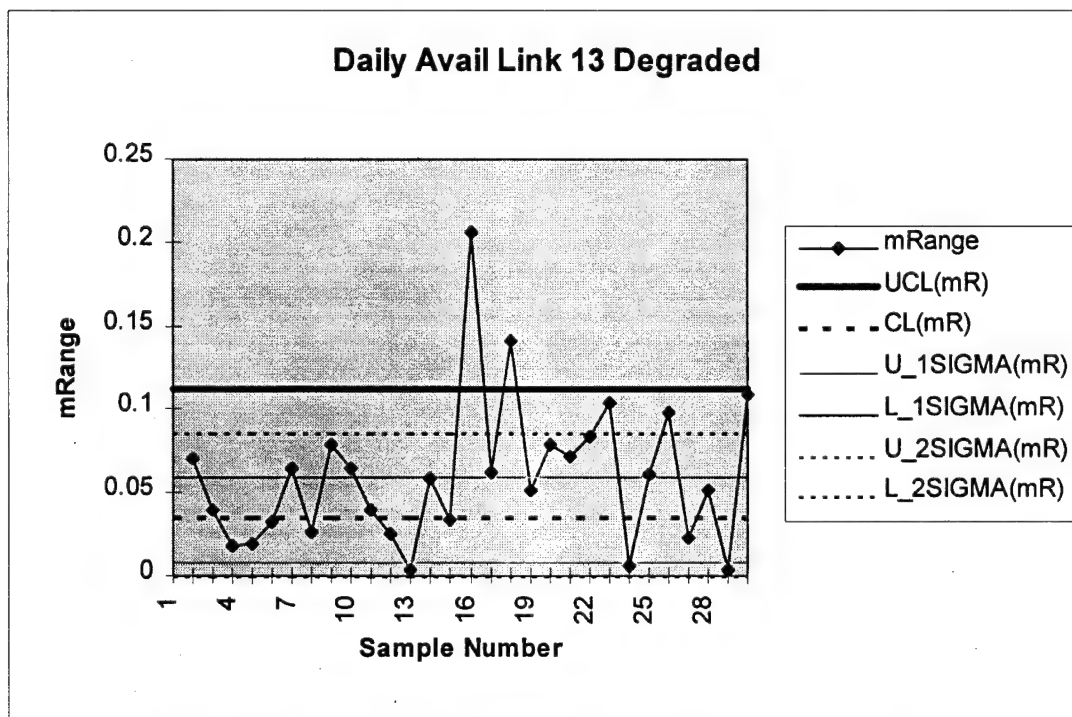
Figure 4.37 mR Chart for Daily Availability link 13 (degraded)
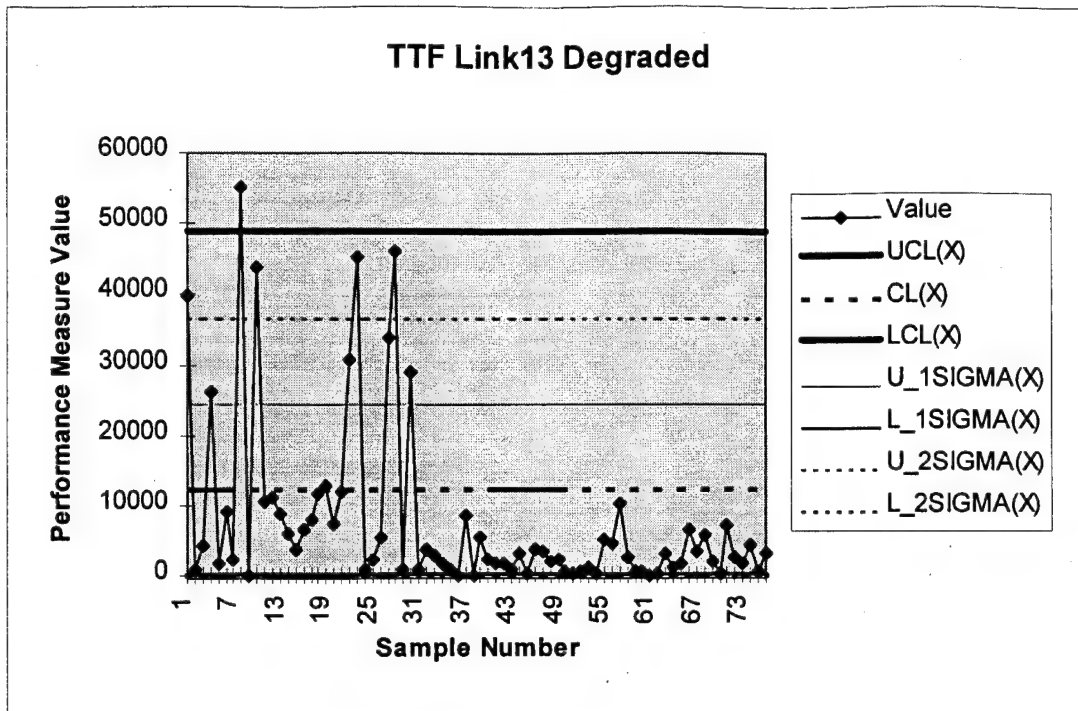
Figure 4.38 X Chart for TTF Link 13 (degraded)
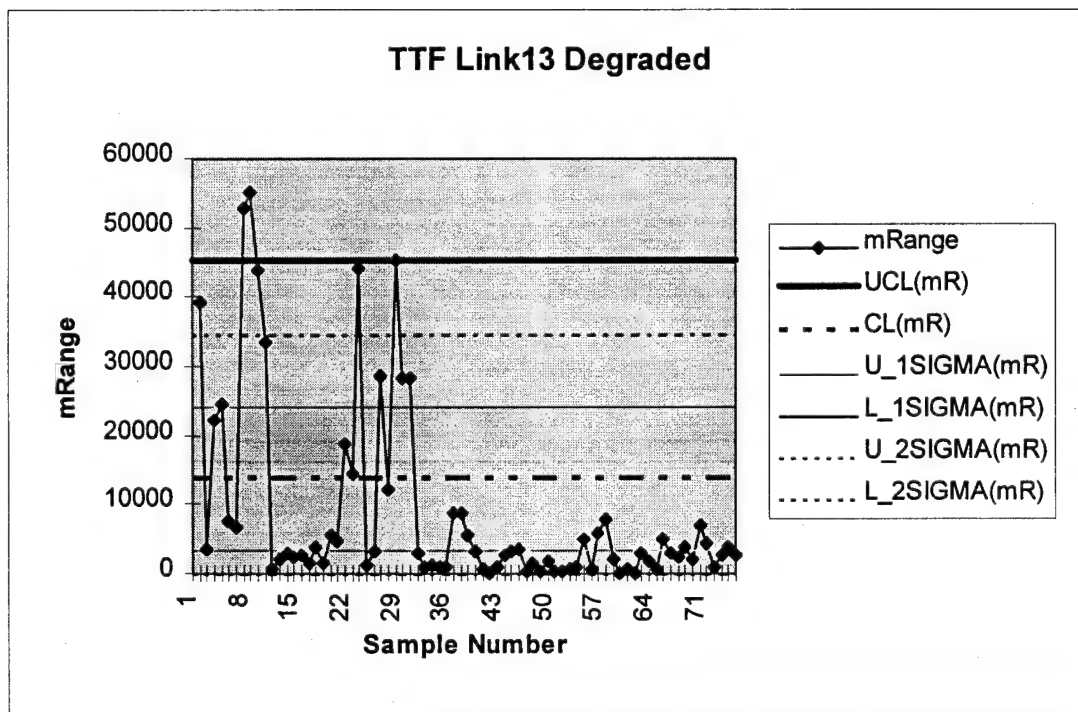
Figure 4.39 mR Chart for TTF Link 13 (degraded)

4.4 Level of Service (LOS) Agreements

In establishing specifications for a LOS Agreement using control charts, there is a very important point regarding the typical relationship between specification limits and control limits as stated by Montgomery: "there is no connection or relationship [mathematical or statistical] between the control limits on the ... charts and the specification limits of the process" (18:213). Control limits are based on the natural variability of a process, while specification limits are determined external from the process (i.e., by management or by a customer) (18:213). Instead, the natural variability of a process defines the natural tolerance limits of the process. These limits are located 3σ above and 3σ below the process mean. So while the control and specification limits are not related, it is helpful to know the inherent process variability before setting specification limits (18:213-14). The empirical rule states that: "Given a homogeneous set of data:

1. Roughly 60% to 75% of the data will be located within $1\ \sigma$ unit on either side of the average.

2. Usually 90% to 98% of the data will be located within $2\ \sigma$ units on either side of the average.

3. Approximately 99% to 100% of the data will be located within $3\ \sigma$ units on either side of the average." (28:61)

where a 'sigma unit' is equal to the standard deviation of the data. Therefore, it is easily seen that the natural tolerance limits of a process contain approximately 99% to 100% of the data from that process.

Using this information, when setting the specification limits on a performance measure, the mean and standard deviation (the standards) of this measure should be known. Therefore, if the theoretical standards are known, they should be used to find the

natural tolerance limits of the performance measure; whereas if the theoretical standards are unknown, they must be estimated from the data in order to determine the natural tolerance limits. Once the natural tolerance limits are known it is recommended that both the upper and lower the specification limits exceed 3σ units from the mean. It this is accomplished, then virtually all of the performance measures will fall within the specification limits as long as it stays reasonably in-control (28:124). If desired, the specification limits may be plotted on a chart of individual measurements (i.e., X chart or p chart) but not on a chart of averages (x-bar chart) (18:214). The specification limits are not limits for the average of the performance measures, they are limits for individual values. Hence, the LOS Agreement specifications for each performance measure, which can be determined by comparison to the natural process limits (+ or - 3σ from the mean), can be plotted on a chart containing the individual values of that performance measure. This facilitates easy monitoring of conformance to those specifications.

4.5 Summary

The performance measures for three monitoring viewpoints, identified in Chapter 2, and their applicable control charts were applied to a case study network. For some measures, more than one chart type was applied and evaluated for appropriateness. The EXCEL spreadsheets and macros containing the control chart procedures in Chapter 3 provided the means for accomplishing this evaluation. Of all the measures evaluated, many seem to be useful indicators of network performance that can be calculated from the data currently being collected from the network (the log of failure and repair times). The overall performance measures: the number of down links (DwnLnk), the proportion of down links (p-down), and the proportion of up links (p-up) all seem to be excellent indicators of the network's status and performance along with the fact that

the data for them is easy to collect. All that is needed is a count of links up or down. Only one of these measures needs to be monitored though since they are all so closed related. The choice is up to the network monitors and what makes the most sense to them. The (s-t) measure p-path is highly variable, and proved to be quite volatile if the 'right combination of links' were to fail at once. But then again, these are the assignable causes that are of interest. In using this measure though, one must beware that there may be false alarms to an out-of-control condition from the inherent variability of the network in relation to the paths.

Finally, the individual link measures of Availability, p-link, and TTF, TTR, and TBF all seem valuable. From the individual level of these measures, a problem link can be monitored on its own to reveal its individual assignable causes for being out-of-control. Also the relationships between TTF, TBF, and TTR can be extremely useful in pinpointing where the cause of an out-of-control condition is coming from (i.e. maintenance problems, degradation problems, etc.).

In addition, two important issues were identified relating to proper control chart construction. These were proper data collection rate and proper subgrouping of this data. If these two procedures are done incorrectly, the control chart will not provide useful information.

5. Conclusions and Recommendations

5.1 Thesis Objectives

The first primary objective of this research was to identify and evaluate possible statistical process control methods (primarily control charts) that could be used to proactively monitor communication network performance over time. This was accomplished through a review and evaluation of previous work in this field in Chapter 2. From this review, several possible performance measures were investigated to represent the reliability, availability, and degradation of the sponsor's communication network over time. An explicit degradation performance measure was not chosen since it can be readily monitored through the other performance measures. These measures were chosen on the basis of their computability from directly observable network data.

Next, control charts were deemed the most appropriate SPC technique for monitoring the chosen the performance measures. Appropriate 'candidate' control charts were identified for each performance measure, and proper procedures for constructing the charts was discussed. A case study was then undertaken to demonstrate control charting techniques as well as appropriateness of the proposed performance measures.

During the case study, a computer simulation was created to generate data representative of the observable data from the sponsor's communication network. This simulation model was based on a queueing model which described the theoretical expected performance of the network. These theoretical insights were then used to develop 'standards' for some of the performance measures' control charts. Other theoretical properties, for example, the binomial distribution, were also used to develop 'standards' for yet more of the measures' control charts. In fact, only the standards of

5-1

one measure, the proportion of operating paths (p-path), needed to be estimated. An investigation of each measure and its control charts provided insights on the 'best' measures and their corresponding 'best' monitoring techniques (i.e., control charts). In addition, degradation monitoring was demonstrated for each appropriate measure.

In accordance with the second primary objective, 'to automate the best of the identified SPC methods into a user friendly software package.' and in order to complete the above analysis, the identified 'best' control charting techniques were incorporated into a software package of EXCEL (8) spreadsheets and macros.

Finally, as required by the third primary objective to relate these SPC methods to LOS Agreements, methods were discussed on possible uses of control charting techniques to establish and monitor LOS Agreements and their specifications.

Overall, various performance measures are available even from the limited data assumed to be observable from the network. The choice of which measure to use depends on which of them is most understandable to the network's controllers. This choice also depends on any specific desires or concerns the network controllers have about the network (i.e., monitoring on an overall network level is preferred to monitoring on a link level since such low-level monitoring of the links has been deemed unnecessary). Alternately, if there is a suspected problem on a certain portion of the network, but the cause is unknown, this specific part of the network (i.e., a specific link or links) may be all that is desired to be monitored. The choice here is user and network 'need dependent.'

5.2 Recommendations

The performance measures identified in this research and the control charting techniques demonstrated are uniquely applicable to the sponsor's need to "proactively

monitor the reliability, availability, and degradation of networks ...," no matter what the end desired result is (i.e., LOS Agreements, regular monitoring, etc.). Control charting is a straightforward method of real-time (or near real-time) monitoring applicable to many different systems and this study provides the sponsor a new means with which to assure the LOS Agreements are fulfilled.

Future research is recommended on CUSUM and EWMA charts for their greater sensitivity to small shifts in a system if this is a concern for the sponsor's network. Also, if any new data from the communication network becomes available, such as time delay or bit error rate, the control chart procedures can be applied to them by following the proper procedures demonstrated. In addition, as this thesis effort was just ending, a new research effort was published by Buchsbaum and Mihail (6). In their paper they propose a heuristic based on Monte Carlo and Markov simulation techniques in order to approximate various reliability parameters of communication networks with link failures (6:117). It is recommended that this new research be investigated for possible application to the sponsor's network. Time did not permit any investigation or application of this paper in the current research effort.

APPENDIX F: Input Network File and Path Enumeration Output

Input Network Description File - Case Study Network

```
41              Number of nodes
77              Number of links
 1 40  55        Origin node / Destination node / Link number
 1  2  56        "
 1  3  57        "
 1  4  58        etc.....
 1  5  59
 1  6  60
40 11   1
 2 11   2
 3  7   3
 4 11   4
 5  8   5
 6  9   6
 7 10   7
 8 11   8
 9 11   9
10 11  10
11 23  11
11 24  12
11 12  13
11 38  14
11 39  15
12 13  16
12 14  17
12 15  18
12 16  19
12 17  20
12 18  21
12 19  22
12 20  23
12 21  24
12 22  25
13 23  26
13 24  27
13 25  28
13 26  29
13 27  30
13 28  31
13 29  32
14 23  33
14 24  34
14 25  35
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14 26 36
14 27 37
14 28 38
14 29 39
15 31 40
15 32 41
16 30 42
16 31 43
16 32 44
16 33 45
16 36 46
17 30 47
17 33 48
17 34 49
18 38 50
19 39 51
20 35 52
21 36 53
22 37 54
23 41 61
24 41 62
25 41 63
26 41 64
27 41 65
28 41 66
29 41 67
30 41 68
31 41 69
32 41 70
33 41 71
34 41 72
35 41 73
36 41 74
37 41 75
38 41 76
39 41 77
```

Factors for constructing variables control charts

| Observations in Sample, n | Chart for Averages | | | Chart for Standard Deviations | | | | | | Chart for Ranges | | | | | | |
| | Factors for Control Limits | | | Factors for Center Line | | Factors for Control Limits | | | | Factors for Center Line | | | Factors for Control Limits | | | |
	A	A_2	A_3	c_4	$1/c_4$	B_3	B_4	B_5	B_6	d_2	$1/d_2$	d_3	D_1	D_2	D_3	D_4
2	2.121	1.880	2.659	0.7979	1.2533	0	3.267	0	2.606	1.128	0.8865	0.853	0	3.686	0	3.267
3	1.732	1.023	1.954	0.8862	1.1284	0	2.568	0	2.276	1.693	0.5907	0.888	0	4.358	0	2.575
4	1.500	0.729	1.628	0.9213	1.0854	0	2.266	0	2.088	2.059	0.4857	0.880	0	4.698	0	2.282
5	1.342	0.577	1.427	0.9400	1.0638	0	2.089	0	1.964	2.326	0.4299	0.864	0	4.918	0	2.115
6	1.225	0.483	1.287	0.9515	1.0510	0.030	1.970	0.029	1.874	2.534	0.3946	0.848	0	5.078	0	2.004
7	1.134	0.419	1.182	0.9594	1.0423	0.118	1.882	0.113	1.806	2.704	0.3698	0.833	0.204	5.204	0.076	1.924
8	1.061	0.373	1.099	0.9650	1.0363	0.185	1.815	0.179	1.751	2.847	0.3512	0.820	0.388	5.306	0.136	1.864
9	1.000	0.337	1.032	0.9693	1.0317	0.239	1.761	0.232	1.707	2.970	0.3367	0.808	0.547	5.393	0.184	1.816
10	0.949	0.308	0.975	0.9727	1.0281	0.284	1.716	0.276	1.669	3.078	0.3249	0.797	0.687	5.469	0.223	1.777
11	0.905	0.285	0.927	0.9754	1.0252	0.321	1.679	0.313	1.637	3.173	0.3152	0.787	0.811	5.535	0.256	1.744
12	0.866	0.266	0.886	0.9776	1.0229	0.354	1.646	0.346	1.610	3.258	0.3069	0.778	0.922	5.594	0.283	1.717
13	0.832	0.249	0.850	0.9794	1.0210	0.382	1.618	0.374	1.585	3.336	0.2998	0.770	1.025	5.647	0.307	1.693
14	0.802	0.235	0.817	0.9810	1.0194	0.406	1.594	0.399	1.563	3.407	0.2935	0.763	1.118	5.696	0.328	1.672
15	0.775	0.223	0.789	0.9823	1.0180	0.428	1.572	0.421	1.544	3.472	0.2880	0.756	1.203	5.741	0.347	1.653
16	0.750	0.212	0.763	0.9835	1.0168	0.448	1.552	0.440	1.526	3.532	0.2831	0.750	1.282	5.782	0.363	1.637
17	0.728	0.203	0.739	0.9845	1.0157	0.466	1.534	0.458	1.511	3.588	0.2787	0.744	1.356	5.820	0.378	1.622
18	0.707	0.194	0.718	0.9854	1.0148	0.482	1.518	0.475	1.496	3.640	0.2747	0.739	1.424	5.856	0.391	1.608
19	0.688	0.187	0.698	0.9862	1.0140	0.497	1.503	0.490	1.483	3.689	0.2711	0.734	1.487	5.891	0.403	1.597
20	0.671	0.180	0.680	0.9869	1.0133	0.510	1.490	0.504	1.470	3.735	0.2677	0.729	1.549	5.921	0.415	1.585
21	0.655	0.173	0.663	0.9876	1.0126	0.523	1.477	0.516	1.459	3.778	0.2647	0.724	1.605	5.951	0.425	1.575
22	0.640	0.167	0.647	0.9882	1.0119	0.534	1.466	0.528	1.448	3.819	0.2618	0.720	1.659	5.979	0.434	1.566
23	0.626	0.162	0.633	0.9887	1.0114	0.545	1.455	0.539	1.438	3.858	0.2592	0.716	1.710	6.006	0.443	1.557
24	0.612	0.157	0.619	0.9892	1.0109	0.555	1.445	0.549	1.429	3.895	0.2567	0.712	1.759	6.031	0.451	1.548
25	0.600	0.153	0.606	0.9896	1.0105	0.565	1.435	0.559	1.420	3.931	0.2544	0.708	1.806	6.056	0.459	1.541

For $n > 25$

$$A = \frac{3}{\sqrt{n}}, \quad A_3 = \frac{3}{c_4\sqrt{n}}, \quad c_4 \approx \frac{4(n-1)}{4n-3},$$

$$B_3 = 1 - \frac{3}{c_4\sqrt{2(n-1)}}, \quad B_4 = 1 + \frac{3}{c_4\sqrt{2(n-1)}}$$

$$B_5 = c_4 - \frac{3}{\sqrt{2(n-1)}}, \quad B_6 = c_4 + \frac{3}{\sqrt{2(n-1)}}$$

APPENDIX B: Steady-State Equations for an M/M/s Queueing Model

M/M/s Model with finite calling population (N)

Assumes: All interarrival times are iid exponential with mean rate λ

All service(repair) times are iid exponential with mean rate μ

N = link population

n = number of links in the queueing system (number of links down) = 0, 1, 2,....,N

s = number of servers (repairmen) = N (in this case)

The software package MATHCAD Version 5.0 Plus was used to solve the steady-state equations for the M/M/s queueing model. The known parameters are:

$$N := \text{number\_of\_links\_in\_network} \qquad n := 0 .. N \qquad \mu := \frac{1}{754}$$

The steady-state equations are (for N = s):

$$P_0 := \frac{1}{\displaystyle\sum_n \frac{N!}{(N-n)! \cdot n!} \cdot \left(\frac{\lambda}{\mu}\right)^n} \qquad\qquad P_n := \frac{N!}{(N-n)! \cdot n!} \cdot \left(\frac{\lambda}{\mu}\right)^n \cdot P_0$$

where P_n is the probability of being in state n (n links are down), and

$$\lambda_{bar} := \sum_{n=0}^{N} (N-n) \cdot \lambda \cdot P_n$$

where λ-bar is the average arrival rate to the queue in the long run, and

$$L_q := \sum_{n=s}^{N} (n-s) \cdot P_n \qquad L := \sum_{n=0}^{N-1} n \cdot P_n + L_q + N \cdot \left(1 - \sum_{n=0}^{N-1} P_n\right)$$

where L_q is the expected queue length (zero in this case since $N = s$) and L is the expected number of links in the queueing system. Solving the λ-bar equation for λ, substituting in the P_n's and N, and then resolving the equation for λ allows λ to be found. However, once the have been substituted, resolving for λ was a task accomplished by MATHCAD and the resulting equation is too large to show on a single page.

Here the λ-bar equation is solved for λ:

$$\lambda_{bar} = \sum_{n=0}^{N} (N-n) \cdot \lambda \cdot P_n$$

$$\lambda_{bar} = N \cdot \lambda \cdot P_0 + (N-1) \cdot \lambda \cdot P_1 + (N-2) \cdot \lambda \cdot P_2 + (N-3) \cdot \lambda \cdot P_3 + \dots + \lambda \cdot P_{N-1}$$

$$\lambda = \frac{-\lambda_{bar}}{-N \cdot P_0 - (N-1) \cdot P_1 - (N-2) \cdot P_2 - (N-3) \cdot P_3 - \dots - P_{N-1}}$$

$$\lambda = \frac{-\lambda_{bar}}{\displaystyle\sum_{n=0}^{N} -(N-n) \cdot P_n}$$

At this point to solve for the value of λ, the P_n's are substituted in as well as the values for and μ, and MATHCAD's symbolic processor takes over by expanding the summations and solving for λ.

M/M/s Model with finite calling population (N = 5)

$\mu = 1/120$ seconds

$N = 5$
$n = 0, 1, 2,...,5$
$s = N = 5$

The equations for the P_n's in Appendix B are expanded for substitution into the λ-bar equa

$$P_0 = \frac{1}{\displaystyle\sum_{n=0}^{5} \frac{5!}{(5-n)! \cdot n!} \left(\frac{\lambda}{\mu}\right)^n} \quad ---\!>> \quad P_0 = \frac{1}{\left(1 + 5 \cdot \frac{\lambda}{\mu} + 10 \cdot \frac{\lambda^2}{\mu^2} + 10 \cdot \frac{\lambda^3}{\mu^3} + 5 \cdot \frac{\lambda^4}{\mu^4} + \frac{\lambda^5}{\mu^5}\right)}$$

$$P_n = \frac{5!}{(5-n)! \cdot n!} \cdot \left(\frac{\lambda}{\mu}\right)^n \cdot P_0$$

$$P_1 = \frac{5!}{(5-1)! \cdot 1!} \cdot \left[\frac{\lambda}{(\mu)}\right]^1 \cdot P_0 \qquad P_2 = \frac{5!}{(5-2)! \cdot 2!} \cdot \left[\frac{\lambda}{(\mu)}\right]^2 \cdot P_0$$

$$P_3 = \frac{N!}{(N-3)! \cdot 3!} \cdot \left[\frac{\lambda}{(\mu)}\right]^3 \cdot P_0 \qquad P_4 = \frac{N!}{(N-4)! \cdot 4!} \cdot \left[\frac{\lambda}{(\mu)}\right]^4 \cdot P_0$$

$$P_5 = \frac{N!}{(N-5)! \cdot 5!} \cdot \left[\frac{\lambda}{(\mu)}\right]^5 \cdot P_0$$

C-1

The Pn's and μ can now be substituted into the λ equation for MATHCAD to solve:

$$\mu = \frac{1}{120} \qquad \lambda = \frac{-\lambda_{bar}}{\left(-5 \cdot P_0 - 4 \cdot P_1 - 3 \cdot P_2 - 2 \cdot P_3 - P_4\right)}$$

$$\lambda = \frac{1}{725}$$

Using the derived value of λ, the numerical vaues for L and the P_n's can now be found:

$$N := 5 \qquad \lambda := \frac{1}{725} \qquad \mu := \frac{1}{120} \qquad L_q := 0$$

$$L := \sum_{n=0}^{N-1} n \cdot P_n + L_q + N \cdot \left(1 - \sum_{n=0}^{N-1} P_n\right) \qquad L = 0.7100591716$$

This value for L is compared to the end-of-simulation (10 months is used here) average number of links down shown in the SLAM II Summary Report as a 'Statistic for Time-Persistent Variable' , LnksDwn (this report is attached at the end of this Appendix).

The mean value for LnksDwn = 0.708. The resulting difference from L is approximately 0 links. Hence these numbers are in agreement.

In addition, the statistics for the Mean Time to Failure for all links 1-5 were collected and compared to the theoretical $1/\lambda = 725$ seconds for agreement:

Mean Value	Difference from $1/\lambda = 725$	Standard Deviation
MTTF_Link1 := 727	$\text{Diff}_1 := 2$	SD_MTTF_Link1 := 726
MTTF_Link2 := 718	$\text{Diff}_2 := 7$	SD_MTTF_Link2 := 718
MTTF_Link3 := 731	$\text{Diff}_3 := 6$	SD_MTTF_Link3 := 736
MTTF_Link4 := 726	$\text{Diff}_4 := 1$	SD_MTTF_Link4 := 729
MTTF_Link5 := 730	$\text{Diff}_5 := 5$	SD_MTTF_Link5 := 741

Since the largest difference among these five sample links is 7 seconds and the theoretical r value is 7 seconds, two orders of magnitude larger, these number also agree. In addition, t standard deviations of the MTTF's are on the same order of magnitude as the mean values supporting the exponential distribution assumption in Appendix B.

Finally, the values for the P_n's are calculated to show that the initial conditions of no links failed, P_0, is at least on the same order of probabilities of all the other states, and, in fact, it the most probable state:

$$P_0 = 0.4649502527$$

$$P_1 = 0.384786416$$

$$P_2 = 0.1273775722$$

$$P_3 = 0.0210831844$$

$$P_4 = 0.0017448153$$

$$P_5 = 0.0000577594$$

SLAM II SUMMARY REPORT

SIMULATION PROJECT NET   BY BORGIA

DATE 11/30/1994   RUN NUMBER   1 OF   1

CURRENT TIME   .2592E+08
STATISTICAL ARRAYS CLEARED AT TIME   .0000E+00

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
MTTF_ALL	.169E+03	.169E+03	.100E+01	.000E+00	.192E+04	****
MTBF1	.846E+03	.735E+03	.869E+00	.200E+01	.679E+04	****
MTTF1	*.727E+03*	*.726E+03*	*.100E+01*	*.000E+00*	*.673E+04*	****
MTTR1	.119E+03	.118E+03	.991E+00	.000E+00	.105E+04	****
MTTR_INST	.120E+03	.686E+00	.571E-02	.115E+03	.235E+03	****
MTTF2	*.718E+03*	*.718E+03*	*.100E+01*	*.000E+00*	*.717E+04*	****
MTTR2	.120E+03	.121E+03	.101E+01	.000E+00	.142E+04	****
MTTF3	*.731E+03*	*.736E+03*	*.101E+01*	*.000E+00*	*.713E+04*	****
MTTR3	.120E+03	.120E+03	.996E+00	.000E+00	.143E+04	****
MTTF4	*.726E+03*	*.729E+03*	*.100E+01*	*.000E+00*	*.835E+04*	****
MTTR4	.119E+03	.119E+03	.998E+00	.000E+00	.141E+04	****
MTTF5	*.730E+03*	*.741E+03*	*.101E+01*	*.000E+00*	*.856E+04*	****
MTTR5	.120E+03	.118E+03	.989E+00	.000E+00	.117E+04	****
MTBF2	.838E+03	.728E+03	.869E+00	.300E+01	.762E+04	****
MTBF3	.851E+03	.745E+03	.875E+00	.200E+01	.725E+04	****
MTBF4	.845E+03	.737E+03	.873E+00	.400E+01	.837E+04	****
MTBF5	.850E+03	.749E+03	.882E+00	.300E+01	.876E+04	****

STATISTICS FOR TIME-PERSISTENT VARIABLES

	MEAN VALUE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME INTERVAL	CURRENT VALUE
LNKSUP	4.292	.837	.00	5.00	*********	4.00
LNKSDWN	*.708*	*.837*	*.00*	*5.00*	*********	*1.00*

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
1					
11	.7068	.8393	5	1	153217

C-4

APPENDIX D: M/M/s Queue Steady-State Results / End-of-Simulation Results
for Case Study Network

<u>M/M/s Model with finite calling population (N = 77)</u>

$\mu = 1/754$ seconds

$N = 77$
$n = 0, 1, 2,...,77$
$s = N = 77$

The equations for the P_n's in Appendix B are expanded and substituted into the λ-bar equation as was shown in Appendix C for the small validation network.

$$P_0 = \frac{1}{\displaystyle\sum_{n=0}^{77} \frac{77!}{(77-n)! \cdot n!} \cdot \left(\frac{\lambda}{\mu}\right)^n} \qquad\qquad P_n = \frac{77!}{(77-n)! \cdot n!} \cdot \left(\frac{\lambda}{\mu}\right)^n \cdot P_0$$

$$\lambda_{bar} = \sum_{n=0}^{77} (77-n) \cdot \lambda \cdot P_n \qquad ---\gg \qquad \lambda = \frac{-\lambda_{bar}}{\displaystyle\sum_{n=0}^{77} -(77-n) \cdot P_n}$$

So then for : $\qquad \mu = \dfrac{1}{754} \qquad --> \qquad \lambda = \dfrac{1}{12259}$

Using the derived value of λ, the numerical vaues for L and the P_n's can now be found:

$$N := 77 \qquad L_q := 0 \qquad \lambda := \frac{1}{12259} \qquad \mu := \frac{1}{754}$$

$$L := \sum_{n=0}^{N-1} n \cdot P_n + L_q + N \cdot \left(1 - \sum_{n=0}^{N-1} P_n\right) \qquad\qquad L = 4.461538$$

This value for L is compared to the end-of-simulation (2 months is used here) average nun of links down shown in the SLAM II Summary Report as a 'Statistic for Time-Persistent Variable', LnksDwn (this report is attached at the end of the Appendix).

The mean value for LnksDwn $= 4.4325$. The resulting difference from L is approximately 0.029 links. Hence these numbers are in agreement.

In addition, the statistics for the Mean Time to Failure for links 2-5 and 16 were collected (chosen arbitrarily) and are compared to the theoretical $1/\lambda = 12259$ seconds for agreemen

Mean Value	Difference from $1/\lambda = 12259$	Standard Deviation
$\text{MTTF\_Link16} := 12200$	$\text{Diff}_{16} := 59$	$\text{SD\_MTTF\_Link16} := 12400$
$\text{MTTF\_Link2} := 12800$	$\text{Diff}_2 := 541$	$\text{SD\_MTTF\_Link2} := 13800$
$\text{MTTF\_Link3} := 12000$	$\text{Diff}_3 := 259$	$\text{SD\_MTTF\_Link3} := 12300$
$\text{MTTF\_Link4} := 12500$	$\text{Diff}_4 := 241$	$\text{SD\_MTTF\_Link4} := 12500$
$\text{MTTF\_Link5} := 12200$	$\text{Diff}_5 := 59$	$\text{SD\_MTTF\_Link5} := 12300$

Since the largest difference among these five sample links is 541 seconds and the theoretica mean value is 12259 seconds, two orders of magnitude larger, these number also agree. In addition, the standard deviations of the MTTF's are on the same order of magnitude as the mean values supporting the exponential distribution assumption in Appendix B.

Finally, the values for the P_n's are calculated to show that the initial conditions of no links failed, P_0, is on the same order of probabilities of the other most probable states:

$$P_0 = 0.010092 \qquad P_{10} = 0.008577$$

$$P_1 = 0.047795 \qquad P_{11} = 0.003213$$

$$P_2 = 0.111708 \qquad P_{12} = 0.001087$$

$$P_3 = 0.171767 \qquad P_{13} = 0.000334$$

$$P_4 = 0.195446 \qquad P_{14} = 0.000094$$

$$P_5 = 0.175508 \qquad P_{15} = 0.000024 \quad \ldots$$

$$P_6 = 0.129537$$

$$P_{20} = 8.919699 \cdot 10^{-9} \quad \ldots$$

$$P_7 = 0.080811$$

$$P_{40} = 0 \quad \ldots$$

$$P_8 = 0.043491$$

$$P_{77} = 0$$

$$P_9 = 0.020508$$

SIMULATION PROJECT NET   BY BORGIA

DATE 4/ 1/1995   RUN NUMBER   1 OF   1

CURRENT TIME   .5184E+07
STATISTICAL ARRAYS CLEARED AT TIME   .0000E+00

STATISTICS FOR VARIABLES BASED ON OBSERVATION

	MEAN VALUE	STANDARD DEVIATION	COEFF. OF VARIATION	MINIMUM VALUE	MAXIMUM VALUE	NO.OF OBS
MTTF_ALL	.170E+03	.170E+03	.998E+00	.000E+00	.192E+04	****
MTBF16	.130E+05	.124E+05	.955E+00	.630E+02	.839E+05	400
MTTF16	*.122E+05*	*.124E+05*	*.101E+01*	*.306E+01*	*.838E+05*	*400*
MTTR16	.740E+03	.834E+03	.113E+01	.100E+01	.604E+04	400
MTTR_INST	.759E+03	.106E+02	.139E-01	.293E+03	.827E+03	****
MTTF2	*.128E+05*	*.138E+05*	*.108E+01*	*.303E+02*	*.980E+05*	*382*
MTTR2	.781E+03	.799E+03	.102E+01	.100E+01	.557E+04	382
MTTF3	*.120E+05*	*.123E+05*	*.103E+01*	*.380E+02*	*.989E+05*	*407*
MTTR3	.722E+03	.741E+03	.103E+01	.500E+00	.530E+04	407
MTTF4	*.125E+05*	*.125E+05*	*.100E+01*	*.258E+02*	*.881E+05*	*391*
MTTR4	.750E+03	.733E+03	.977E+00	.125E+01	.438E+04	391
MTTF5	*.122E+05*	*.123E+05*	*.101E+01*	*.113E+02*	*.842E+05*	*398*
MTTR5	.769E+03	.754E+03	.981E+00	.319E+01	.383E+04	398
MTBF2	.136E+05	.138E+05	.102E+01	.245E+03	.985E+05	382
MTBF3	.127E+05	.123E+05	.971E+00	.880E+02	.990E+05	407
MTBF4	.132E+05	.125E+05	.946E+00	.156E+03	.892E+05	391
MTBF5	.130E+05	.123E+05	.948E+00	.444E+03	.855E+05	398
LKS_UP_300	.726E+02	.211E+01	.291E-01	.630E+02	.770E+02	****
LKS_DWN_300	.445E+01	.211E+01	.475E+00	.000E+00	.140E+02	****
PATHS_DWN_300	.622E+02	.410E+02	.660E+00	.000E+00	.194E+03	****

STATISTICS FOR TIME-PERSISTENT VARIABLES

	MEAN VALUE	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	TIME INTERVAL	CURRENT VALUE
LNKSUP	72.550	2.111	62.00	77.00	*********	72.00
LNKSDWN	*4.450*	*2.111*	*.00*	*15.00*	**********	*5.00*

REGULAR ACTIVITY STATISTICS

ACTIVITY INDEX/LABEL	AVERAGE UTILIZATION	STANDARD DEVIATION	MAXIMUM UTIL	CURRENT UTIL	ENTITY COUNT
1	4.4504	2.1114	15	5	30498

EXPON(169)

169

INF   1   1

XX(1) = XX(1)+1

XX(2) = ATRIB(1)-XX(18)

XX(18) = ATRIB(1)

1

XX(2)   MTTF_ALL   1

ATRIB(2) = UNFRM(0,77)   1

PKLNK

0,XX(3).EQ.1

1   1   1

0,XX(3).EQ.2

0,XX(3).EQ.0

INF

WARN

SLAM II Network Model - Graphic Representation - Page 1

E-1

RPAI

XX(21) | MTBF1 | 1
XX(22) | MTBF2 | 1
XX(23) | MTBF3 | 1
XX(24) | MTBF4 | 1
XX(25) | MTBF5 | 1

$XX(15) = XX(15)+1$
$XX(16) = XX(16)-1$
1

$0,XX(20).EQ.1$
$0,XX(20).EQ.2$
$0,XX(20).EQ.3$
$0,XX(20).EQ.4$
$0,XX(20).EQ.5$
$0,XX(20).EQ.0$

2 | 1

$ATRIB(4),1$

1

$ATRIB(4) = EXPON(754)$ | 1

RPAIR

SLAM II Network Model - Graphic Representation - Page 2

XX(31) | MTTR1 | 1
XX(32) | MTTR2 | 1
XX(33) | MTTR3 | 1
XX(34) | MTTR4 | 1
XX(35) | MTTR5 | 1

XX(26) | MTTF1 | 1
XX(27) | MTTF2 | 1
XX(28) | MTTF3 | 1
XX(29) | MTTF4 | 1
XX(30) | MTTF5 | 1

0,XX(20).EQ.1
0,XX(20).EQ.2
0,XX(20).EQ.3
0,XX(20).EQ.4
0,XX(20).EQ.5
0,XX(20).EQ.0

XX(7) | MTTR_INST | 1

XX(15) = XX(15)-1 | 1
XX(16) = XX(16)+1

INF

SLAM II Network Model - Graphic Representation - Page 3

SLAM II Network Model - Graphic Representation - Page 4

SLAM II Network Model - Statement Representation

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ARRAY(68,22);
ARRAY(69,22);
ARRAY(70,22);
ARRAY(71,22);
ARRAY(72,22);
ARRAY(73,22);
ARRAY(74,22);
ARRAY(75,22);
ARRAY(76,22);
ARRAY(77,22);
TIMST,XX(16),LNKSUP;
TIMST,XX(15),LNKSDWN;
NETWORK;
INITIALIZE,,7776000,Y;
MONTR,SUMRY,2592000,2592000;
FIN;
```

```
;FILE NET.NET, NODE LABEL SEED ZAAA
;
      CREATE,EXPON(169),169,1,,1;
      ACTIVITY;
      ASSIGN,XX(1)=XX(1)+1,XX(2)=ATRIB(1)-XX(18),XX(18)=ATRIB(1),1;
      ACTIVITY;
      COLCT,XX(2),MTTF_ALL,,1;
      ACTIVITY;
PKLNK ASSIGN,ATRIB(2)=UNFRM(0,77),1;
      ACTIVITY;
      EVENT,1,1;
      ACTIVITY,,XX(3).EQ.0;
      ACTIVITY,,XX(3).EQ.2,WARN;
      ACTIVITY,,XX(3).EQ.1,PKLNK;
      ASSIGN,XX(15)=XX(15)+1,XX(16)=XX(16)-1,1;
      ACTIVITY,,XX(20).EQ.1;
      ACTIVITY,,XX(20).EQ.2,ZAAG;
      ACTIVITY,,XX(20).EQ.3,ZAAH;
      ACTIVITY,,XX(20).EQ.4,ZAAI;
      ACTIVITY,,XX(20).EQ.5,ZAAJ;
      ACTIVITY,,XX(20).EQ.0,RPAI;
      COLCT,XX(21),MTBF16,,1;
      ACTIVITY;
RPAIR ASSIGN,ATRIB(4)=EXPON(754),1;
      ACTIVITY;
      EVENT,6,1;
      ACTIVITY/1,ATRIB(4);
      EVENT,2,1;
      ACTIVITY,,XX(20).EQ.1;
      ACTIVITY,,XX(20).EQ.2,ZAAC;
      ACTIVITY,,XX(20).EQ.3,ZAAD;
      ACTIVITY,,XX(20).EQ.4,ZAAE;
      ACTIVITY,,XX(20).EQ.5,ZAAF;
      ACTIVITY,,XX(20).EQ.0,ZAAB;
      COLCT,XX(26),MTTF16,,1;
      ACTIVITY;
      COLCT,XX(31),MTTR16,,1;
      ACTIVITY;
ZAAB  COLCT,XX(7),MTTR_INST,,1;
      ACTIVITY;
      ASSIGN,XX(15)=XX(15)-1,XX(16)=XX(16)+1,1;
      ACTIVITY;
      TERMINATE;
ZAAC  COLCT,XX(27),MTTF2,,1;
      ACTIVITY;
      COLCT,XX(32),MTTR2,,1;
      ACTIVITY,,,ZAAB;
ZAAD  COLCT,XX(28),MTTF3,,1;
```

```
    ACTIVITY;
    COLCT,XX(33),MTTR3,,1;
    ACTIVITY,,,ZAAB;
ZAAE COLCT,XX(29),MTTF4,,1;
    ACTIVITY;
    COLCT,XX(34),MTTR4,,1;
    ACTIVITY,,,ZAAB;
ZAAF COLCT,XX(30),MTTF5,,1;
    ACTIVITY;
    COLCT,XX(35),MTTR5,,1;
    ACTIVITY,,,ZAAB;
ZAAG COLCT,XX(22),MTBF2,,1;
    ACTIVITY,,,RPAI;
ZAAH COLCT,XX(23),MTBF3,,1;
    ACTIVITY,,,RPAI;
ZAAI COLCT,XX(24),MTBF4,,1;
    ACTIVITY,,,RPAI;
ZAAJ COLCT,XX(25),MTBF5,,1;
    ACTIVITY,,,RPAI;
WARN TERMINATE;
;
    CREATE,300,300,,,1;
    ACTIVITY;
    EVENT,3,1;
    ACTIVITY;
    COLCT,XX(9),LKS_UP_300,,1;
    ACTIVITY;
    COLCT,XX(10),LKS_DWN_300,,1;
    ACTIVITY;
    COLCT,XX(14),PATHS_DWN_300,,1;
    ACTIVITY;
    TERMINATE;
;
    CREATE,3600,3600,,,1;
    ACTIVITY;
    EVENT,4,1;
    ACTIVITY;
    TERMINATE;
;
    CREATE,86400,86400,,,1;
    ACTIVITY;
    EVENT,5,1;
    ACTIVITY;
    TERMINATE;
    END;
```

FORTRAN Insert Code

```
C
C              SLAM VARIABLES
C
C
C ATRIB(1)=TIME OF LINK FAILURE
C ATRIB(2)=LINK IDENTIFICATION #
C
C
C XX(1)=TOTAL LINKS FAILED
C XX(2)=TIME BETWEEN FAILURES (ALL LINKS)
C XX(3)=BRANCHING VARIABLE
C       (1=chosen link is up, 0=chosen link is already failed)
C XX(4)=TOTAL LINKS REPAIRED
C XX(5)=TOTAL DOWN TIME (ALL LINKS)
C XX(6)=MTTF (CUMULATIVE - ALL LINKS)
C XX(7)=MTTR (CUMULATIVE - ALL LINKS)
C XX(8)=AVAILABILITY (CUMULATIVE - ALL LINKS)
C       (A = MTTF/MTTF+MTTR)
C XX(9)=# UP LINKS / STATE  (STATE IS CHECKED EVERY 300 SECONDS)
C XX(10)=# DOWN LINKS / STATE
C XX(11)=NETWORK AVAILABILITY (CALCULATED EVERY 300 SECONDS)
C       (A=P=# UP LINKS/TOTAL LINKS)
C XX(13)=# UP PATHS FROM (s-t) / STATE
C XX(14)=# DOWN PATHS FROM (s-t) / STATE
C XX(15)=# DOWN LINKS - CONTINUOUS
C XX(16)=# UP LINKS - CONTINUOUS
C XX(17)=NETWORK UNAVAILABILITY (CALCULATED EVERY 300 SECONDS)
C       (A=P=# DOWN LINKS/TOTAL LINKS)
C XX(20)=BRANCHING VARIABLE
C XX(21)=MTBF LINK 1
C XX(22)=MTBF LINK 2
C XX(23)=MTBF LINK 3
C XX(24)=MTBF LINK 4
C XX(25)=MTBF LINK 5
C XX(26)=MTTF LINK 1
C XX(27)=MTTF LINK 2
C XX(28)=MTTF LINK 3
C XX(29)=MTTF LINK 4
C XX(30)=MTTF LINK 5
C XX(31)=MTTR LINK 1
C XX(32)=MTTR LINK 2
C XX(33)=MTTR LINK 3
C XX(34)=MTTR LINK 4
C XX(35)=MTTR LINK 5
```

```
C
C
C       ALL ARRAYS ARE PER LINK VARIABLES
C
C  ARRAY(LINK #,1)=LINK STATUS   (1 = up, 0 = down)
C  ARRAY(LINK #,2)=TOTAL TIME BETWEEN FAILUES (TBF)
C  ARRAY(LINK #,3)=TOTAL # FAILURES  (CLEARED HOURLY)
C  ARRAY(LINK #,4)=TOTAL DOWN TIME   (CLEARED HOURLY)
C  ARRAY(LINK #,5)=TOTAL "UP" STATES (CLEARED HOURLY)
C                   (STATES ARE CHECKED EVERY 300 SECONDS)
C  ARRAY(LINK #,6)=LINK AVAILABILITY (CLEARED HOURLY)
C             (A=P=UP TIME/TOTAL TIME)
C  ARRAY(LINK #,7)=LINK AVAILABILITY (CLEARED HOURLY)
C             (A=P=UP STATES/TOTAL STATES)
C  ARRAY(LINK #,8)=TOTAL UP TIME    (CLEARED DAILY)
C  ARRAY(LINK #,9)=TOTAL "UP" STATES (CLEARED DAILY)
C  ARRAY(LINK #,10)=LINK AVAILABILITY (CLEARED DAILY)
C             (A=P=UP TIME/TOTAL TIME)
C  ARRAY(LINK #,11)=LINK AVAILABILITY (CLEARED DAILY)
C             (A=P=UP STATES/TOTAL STATES)
C  ARRAY(LINK #,12)=TOTAL FAILURES   (CLEARED DAILY)
C  ARRAY(LINK #,13)=TOTAL DOWN TIME (TTR)  (CLEARED DAILY)
C  ARRAY(LINK #,14)=PREVIOUS LINK FAILURE TIME
C  ARRAY(LINK #,15)=MTBF
C  ARRAY(LINK #,16)=MTTR
C  ARRAY(LINK #,17)=CUMULATIVE LINK AVAILABILITY
C             (A= LINK MTTF/LINK MTTF+LINK MTTR)
C  ARRAY(LINK #,18)=TOTAL # FAILURES  (RUNNING TOTAL)
C  ARRAY(LINK #,19)=TOTAL # REPAIRS
C  ARRAY(LINK #,20)=TIME REPAIR IS COMPLETED
C  ARRAY(LINK #,21)=TOTAL TTF
C  ARRAY(LINK #,22)=MTTF
```

```
      SUBROUTINE INTLC
$INCLUDE: 'PARAM.INC'
$INCLUDE: 'SCOM1.COM'
   parameter (maxn=50)
   parameter (maxa=10)
   parameter (maxp=200)
   integer nn,na,np,num(maxn,maxn)
   integer arc(maxn,0:maxa),path(maxp,0:maxn),LKPATH(maxp,0:maxn)
   integer HOUR,CNT,CTR,D,DY,DA,CT,WARN,LINKS
   real BTWF,DLYUP,LNKDWN,NUMFL,LKUP,DYUP,FAIL,DLYDWN
   common/ONE/NUMFL,LKUP,DYUP,BTWF,DLYUP,LNKDWN,FAIL,HOUR,CNT,CTR
  c,D,DY,DA,CT,DLYDWN,WARN,LINKS
   common/network/nn,na,np,arc,path,num,LKPATH
   EXTERNAL INPUT,ENUMPATH
   OPEN(UNIT=3,FILE='1G3HRL.OUT')
   OPEN(UNIT=5,FILE='1G3DLY.OUT')
   OPEN(UNIT=8,FILE='1LRUN.OUT')
   OPEN(UNIT=9,FILE='1LNKAV.OUT')
   OPEN(UNIT=10,FILE='1TBF.OUT')
   OPEN(UNIT=11,FILE='1STATE.OUT')
   OPEN(UNIT=12,FILE='1MTBF.OUT')
   OPEN(UNIT=13,FILE='1TTF.OUT')
   OPEN(UNIT=14,FILE='1TTR.OUT')
   OPEN(UNIT=15,FILE='1MTTF.OUT')
   OPEN(UNIT=16,FILE='1MTTR.OUT')
   OPEN(UNIT=17,FILE='1REL.OUT')
   WRITE(3,600) '      HOURLY CALCULATIONS PER LINK'
   WRITE(3,600) 'HOUR  LINK    FAILS UP-CHECKS    UP-TIME DOWN-TI
  cME   AVAIL-TIM  AVAIL-CONF'
   WRITE(5,600) '      DAILY CALCULATIONS PER LINK'
   WRITE(5,600) 'DAY   LINK     FAILS UP-CHECKS    UP-TIME DOWN-
  cTIME  AVAIL-TIM  AVAIL-CONF'
   WRITE(9,600) 'LINK  AVAILABILITY'
   WRITE(10,600) '      LINK TBF'
   WRITE(11,600) '      EVERY 300 SECOND STATE CHECKS'
   WRITE(11,600) ' UP-LNKS  DWN-LNKS  P_UP = UP-LNKS/TTL LNKS  P_DWN =
  cDWN-LINKS/TTL LNKS'
   WRITE(12,600) '      LINK MTBF'
   WRITE(13,600) '      LINK TTF'
   WRITE(14,600) '      LINK TTR'
   WRITE(15,600) '      LINK MTTF'
   WRITE(16,600) '      LINK MTTR'
   WRITE(17,600) 'PROPORTION OF UP-PATHS FOR GIVEN (s-t) EVERY 300 SEC'
   NUMFL=0.0
   LKUP=0.0
   DYUP=0.0
   FAIL=0.0
   HOUR=0
   DAY=0
```

E-11

```
        CNT=0
        CTR=287
        D=0
        DY=0
        DA=0
        CT=23
        WARN=0
        DUPATH=0.0
        HUPATH=0.0
        BTWF=0.0
        DLYUP=0.0
        LNKDWN=0.0
        DLYDWN=0.0
        LINKS=77
        xx(16)=links
        DO 100 L=1,LINKS
          CALL PUTARY(L,1,1.0)
100  CONTINUE
        CALL INPUT()
        CALL ENUMPATH()
600  FORMAT(/1X,A/)
        RETURN
        END


subroutine input()
c
      parameter (maxn=50)
      parameter (maxa=10)
      parameter (maxp=200)
      integer nn,na,np,num(maxn,maxn)
      integer arc(maxn,0:maxa),path(maxp,0:maxn),LKPATH(maxp,0:maxn)
      common/network/nn,na,np,arc,path,num,LKPATH
c
      integer i,o,d,lknum
c
      open(unit=20,file='net.dat')
      read(20,'(i2)') nn
      read(20,'(i3)') na
      do 100 i=1,nn
        arc(i,0)=0
100  continue
      do 200 i=1,na
        read(20,10) o,d,lknum
10     format(i2,1x,i2,1x,i3)
        arc(o,0)=arc(o,0)+1
        arc(o,arc(o,0))=d
        num(o,d)=lknum
200  continue
      close(20)
      return
      end
```

```
      subroutine enumpath()
c
      parameter (maxn=50)
      parameter (maxa=10)
      parameter (maxp=200)
      integer nn,na,np,num(maxn,maxn)
      integer arc(maxn,0:maxa),path(maxp,0:maxn),LKPATH(maxp,0:maxn)
      common/network/nn,na,np,arc,path,num,LKPATH
c
      integer i,j,flag,level,done,nodes(maxn),tree(maxn,0:maxa)
      INTEGER N,X,Y,NLINKS,P,NODE
      external fathom
c
      done=0
      level=1
      np=0
      do 100 i=1,nn
        tree(i,0)=0
        nodes(i)=0
100   continue
      tree(1,0)=arc(1,0)
      nodes(1)=1
      nodes(arc(1,arc(1,0)))=1
      do 200 j=1,arc(1,0)
        tree(1,j)=arc(1,j)
200   continue
      call fathom(tree,level,nodes)
400   continue
      if(nodes(nn).eq.1) then
        np=np+1
        path(np,0)=level+1
        path(np,1)=1
        do 500 j=2,path(np,0)
          path(np,j)=tree(j-1,tree(j-1,0))
500     continue
      endif
      if(tree(level,0).ne.0) then
        nodes(tree(level,tree(level,0)))=0
        tree(level,0)=tree(level,0)-1
      endif
      if(tree(level,0).ne.0) then
        nodes(tree(level,tree(level,0)))=1
        call fathom(tree,level,nodes)
      endif
      if(tree(level,0).eq.0) then
        flag=0
300     continue
```

```fortran
      if(level.ne.1) then
        level=level-1
        nodes(tree(level,tree(level,0)))=0
        tree(level,0)=tree(level,0)-1
      endif
      if(level.eq.1) then
        flag=1
      endif
      if(tree(level,0).ne.0) then
        nodes(tree(level,tree(level,0)))=1
        call fathom(tree,level,nodes)
        flag=1
      endif
      if(flag.eq.0) go to 300
      if(level.eq.1) then
        if(tree(level,0).eq.0) then
          done=1
        endif
      endif
      endif
      if(done.eq.0) go to 400
c     open(unit=19,file='1npath.out')
c     write(19,*)'Depth First Path Enumeration -- By Node Number'
c     do 600 i=1,np
c     write(19,10)'There are ',path(i,0),' nodes in path number ',i
c     write(19,20)'          ',(path(i,j),j=1,path(i,0))
c 600 continue
c     close(19)
C
C BUILD LKPATH -- SHOWS PATH BY LINK NUMBER
      DO 700 P=1,np
        NLINKS=0
        N=path(P,0)
        DO 800 NODE=1,N-1
          X=path(P,NODE)
          Y=path(P,NODE+1)
          LKPATH(P,NODE)=NUM(X,Y)
          NLINKS=NLINKS+1
 800    CONTINUE
        LKPATH(P,0)=NLINKS
 700  CONTINUE
      open(unit=18,file='1lpath.out')
      write(18,*)'Depth First Path Enumeration -- By Link Number'
      do 900 i=1,np
        write(18,10)'There are ',lkpath(i,0),' links in path number ',i
 10     format(/1x,a10,i2,a22,i4)
        write(18,20)'          ',(lkpath(i,j),j=1,lkpath(i,0))
 20     format(1x,a10,20i3//)
 900  continue
      close(18)
      return
      end
```

E-14

```fortran
      subroutine fathom(tree,level,nodes)
c
      parameter (maxn=50)
      parameter (maxa=10)
      parameter (maxp=200)
      integer tree(maxn,0:maxa),level,nodes(maxn)
      integer nn,na,np,num(maxn,maxn)
      integer arc(maxn,0:maxa),path(maxp,0:maxn),LKPATH(maxp,0:maxn)
      common/network/nn,na,np,arc,path,num,LKPATH
c
      integer i,j,flag
c
 200  continue
      flag=0
      i=tree(level,tree(level,0))
      if(arc(i,0).ne.0) then
       level=level+1
       do 300 j=1,arc(i,0)
         if(nodes(arc(i,j)).eq.0) then
           tree(level,0)=tree(level,0)+1
           tree(level,tree(level,0))=arc(i,j)
           flag=1
         endif
 300     continue
       if(tree(level,0).ne.0) then
         nodes(tree(level,tree(level,0)))=1
       endif
      endif
      if(nodes(nn).eq.1) then
        flag=0
      endif
      if(flag.eq.1) go to 200
      return
      end
```

```
      SUBROUTINE EVENT(I)
$INCLUDE: 'PARAM.INC'
$INCLUDE: 'SCOM1.COM'
      parameter (maxn=50)
      parameter (maxa=10)
      parameter (maxp=200)
      integer nn,na,np,num(maxn,maxn)
      integer arc(maxn,0:maxa),path(maxp,0:maxn),LKPATH(maxp,0:maxn)
      integer LINKS,LINK,LNK,J,LK,LNKSTS,HOUR,I,L,CNT,CTR,LS,D,
     cDY,DA,CT,WARN,DWN,STS,PTH,LKS,LNKNUM
      real LNKTIM,LNKBTW,LNKDWN,BTWF,LNKUP,AVAIL,DLYUP,AVBL,AVTIM,
     cAVCONF,DOWN,NUMFL,LKUP,DYUP,FAIL,NFAIL,DLYDWN,LAST,BETW,MTTFLK,
     cMTTRLK,AVLK,N,NUMRP,TTF,BACKUP,TTR,MTBFLK,LNKTTF,REL,STATUS
      common/ONE/NUMFL,LKUP,DYUP,BTWF,DLYUP,LNKDWN,FAIL,HOUR,CNT,CTR
     c,D,DY,DA,CT,DLYDWN,WARN,LINKS
      common/network/nn,na,np,arc,path,num,LKPATH
      GO TO (1,2,3,4,5),I
***************************************************************
* LINK HAS BEEN CHOSEN TO FAIL - THIS EVENT SETS LINK STATUS TO DOWN
***************************************************************
1     CONTINUE
      DO 10 LINK=1,LINKS
       J=LINK-1
       IF ((ATRIB(2).GT.J).AND.(ATRIB(2).LE.LINK)) THEN
C
C IF THE LINK IS ALREADY FAILED, A NEW LINK MUST BE CHOSEN
C
       LNK=GETARY(LINK,1)
       IF (LNK.EQ.0.0) THEN
C
C COUNT TOTAL DOWN LINKS TO CHECK FOR ALL LINKS DOWN CONDITION
C
       DO 15 L=1,LINKS
        LNKSTS=GETARY(L,1)
        IF (LNKSTS.EQ.0.0) CNT=CNT+1
15      CONTINUE
       IF (CNT.GE.LINKS) THEN
        XX(3)=2.0
        XX(1)=XX(1)-1
*       WRITE(8,600) 'WARNING -- ALL LINKS HAVE FAILED!'
        WARN=WARN+1
*       READ(*,'(A)')
        CNT=0
        GO TO 100
       END IF
       XX(3)=1.0
       CNT=0
       GO TO 100
```

E-16

```fortran
C
C CHOSEN LINK IS FAILED
C
      ELSE
       CALL PUTARY(LINK,1,0.0)
       LS=GETARY(LINK,1)
C
C CALC TOTAL TIME BETWEEN EACH LINK'S FAILURES  (RUNNING TOTALS)
C
       LNKTIM=GETARY(LINK,14)
       LNKBTW=GETARY(LINK,2)
       BETW=ATRIB(1)-LNKTIM
       LNKBTW=LNKBTW+BETW
       CALL PUTARY(LINK,2,LNKBTW)
C
C WRITE LINK'S TIME BETWEEN FAILURES TO FILE
C
       WRITE(10,606) LINK,BETW
C
C COLLECT TBF PER LINK FOR MTBF (FOR SIM VALIDATION)
C
      IF (LINK.EQ.16) THEN
       XX(21)=BETW
       XX(20)=1
      ELSE
       IF (LINK.EQ.2) THEN
        XX(22)=BETW
        XX(20)=2
       ELSE
        IF (LINK.EQ.3) THEN
         XX(23)=BETW
         XX(20)=3
        ELSE
         IF (LINK.EQ.4) THEN
          XX(24)=BETW
          XX(20)=4
         ELSE
          IF (LINK.EQ.5) THEN
           XX(25)=BETW
           XX(20)=5
          ELSE
           XX(20)=0
          END IF
         END IF
        END IF
       END IF
      END IF
```

```
C
C SAVE LAST FAILURE TIME FOR NEXT BETWEEN CALC
C
      LAST=ATRIB(1)
      CALL PUTARY(LINK,14,LAST)
C
C COUNT EACH LINK'S NUMBER OF FAILURES  (CLEARED HOURLY)
C
      N=GETARY(LINK,3)
      N=N+1
      CALL PUTARY(LINK,3,N)
C
C COUNT EACH LINK'S NUMBER OF FAILURES (RUNNING TOTAL)
C
      NUMFL=GETARY(LINK,18)
      NUMFL=NUMFL+1
      CALL PUTARY(LINK,18,NUMFL)
C
C CALC MTBF FOR THE FAILING LINK AND WRITE TO FILE  (CUMULATIVE)
C
      MTBFLK=LNKBTW/NUMFL
      CALL PUTARY(LINK,15,MTBFLK)
      WRITE(12,606) LINK,MTBFLK
C
C COLLECT TOTAL TIME BETWEEN ALL LINK FAILURES
C
      BTWF=BTWF+XX(2)
C
C RETURN TO NETWORK
C
      ATRIB(3)=LINK
      XX(3)=0
      CNT=0
      GO TO 100
    END IF
   END IF
10  CONTINUE
100 RETURN
******************************************************************
* THE LINK HAS BEEN REPAIRED - THIS EVENT SETS LINK STATUS TO UP
******************************************************************
2   CONTINUE
   LK=ATRIB(3)
   CALL PUTARY(LK,1,1.0)
C
C COUNT NUMBER OF LINKS REPAIRED
C
   XX(4)=XX(4)+1
```

```
C
C CALC EACH LINK'S TOTAL DOWN TIME
C
      DOWN=TNOW-ATRIB(1)
      LNKDWN=GETARY(LK,4)
      LNKDWN=LNKDWN+DOWN
      CALL PUTARY(LK,4,LNKDWN)
C
C COUNT EACH LINK'S NUMBER OF REPAIRS (RUNNING TOTAL)
C
      NUMRP=GETARY(LK,19)
      NUMRP=NUMRP+1
      CALL PUTARY(LK,19,NUMRP)
C
C CALC MTTR FOR THE REPAIRED LINK AND WRITE TO FILE  (CUMULATIVE)
C
      MTTRLK=LNKDWN/NUMRP
      CALL PUTARY(LK,16,MTTRLK)
      WRITE(16,606) LK,MTTRLK

C
C COLLECT TOTAL DOWN/REPAIR TIME (ALL LINKS)
C
      XX(5)=XX(5)+DOWN
C
C CALC LINK'S TIME TO FAILURE AND COLLECT LINK'S TOTAL TTF (RUNNING TOTALS)
C
      BACKUP=GETARY(LK,20)
      TTF=ATRIB(1)-BACKUP
      LNKTTF=GETARY(LK,21)
      LNKTTF=LNKTTF+TTF
      CALL PUTARY(LK,21,LNKTTF)
C
C SAVE LINK'S BACK-UP TIME FOR NEXT TTF CALC
C
      CALL PUTARY(LK,20,TNOW)
C
C WRITE LINK'S TTF TO FILE AND TTR TO FILE
C
      TTR=DOWN
      WRITE(13,606) LK,TTF
      WRITE(14,606) LK,TTR
C
C COLLECT TTF PER LINK FOR MTTF AND TTR PER LINK FOR MTTR  (FOR SIM VALIDATE)
C
      IF (LK.EQ.16) THEN
       XX(26)=TTF
       XX(31)=TTR
       XX(20)=1
      ELSE
```

```fortran
      IF (LK.EQ.2) THEN
        XX(27)=TTF
        XX(32)=TTR
        XX(20)=2
      ELSE
        IF (LK.EQ.3) THEN
          XX(28)=TTF
          XX(33)=TTR
          XX(20)=3
        ELSE
          IF (LK.EQ.4) THEN
            XX(29)=TTF
            XX(34)=TTR
            XX(20)=4
          ELSE
            IF (LK.EQ.5) THEN
              XX(30)=TTF
              XX(35)=TTR
              XX(20)=5
            ELSE
              XX(20)=0
            END IF
          END IF
        END IF
      END IF
      END IF
C
C CALC MTTF FOR THE FAILING LINK AND WRITE TO FILE   (CUMULATIVE)
C
      NUMFL=GETARY(LK,18)
      MTTFLK=LNKTTF/NUMFL
      CALL PUTARY(LK,22,MTTFLK)
      WRITE(15,606) LK,MTTFLK
C
C CALC CUMULATIVE AVAIL FOR THE REPAIRED LINK
C
      AVLK=MTTFLK/(MTTFLK+MTTRLK)
      CALL PUTARY(LK,17,AVLK)
      WRITE(9,601) LK,AVLK
C
C CALC MTTF - INSTANTANEOUS ALL LINKS
C
      XX(6)=LNKTTF/XX(1)
C
C CALC MTTR - INSTANTANEOUS ALL LINKS
C
      XX(7)=XX(5)/XX(4)
C
C CALC AVAILABILITY USING MTTF AND MTTR - INSTANTANEOUS ALL LINKS
C
      XX(8)=XX(6)/(XX(6)+XX(7))
      RETURN
```

E-20

```
*****************************************************
* CHECK STATE EVERY 300 SECONDS
*****************************************************
 3   CONTINUE
     XX(9)=0
     DO 30 L=1,LINKS
C
C COUNT TOTAL "UP" LINKS (GOAL #2)
C
     LNKSTS=GETARY(L,1)
     IF (LNKSTS.EQ.1.0) THEN
       XX(9)=XX(9)+1
C
C COUNT "UP"s FOR P CALC  (GOAL #3)
C
       LKUP=GETARY(L,5)
       LKUP=LKUP+1
       CALL PUTARY(L,5,LKUP)
     END IF
 30  CONTINUE
C
C COLLECT NUMBER OF LINKS DOWN AT EACH STATE
C
     XX(10)=LINKS-XX(9)
C
C CALC AVAILABILITY AS P = # LINKS UP/TOTAL LINKS (GOAL #2)
C
     XX(11)=XX(9)/LINKS
C
C CALC AVAILABILITY AS P = # LINKS DOWN/TOTAL LINKS (GOAL #2)
C
     XX(17)=XX(10)/LINKS
C
C WRITE 300 SEC CHECKS TO FILE
C
     CTR=CTR+1
     IF (CTR.EQ.288) THEN
       D=D+1
       WRITE(11,605) 'DAY = ',D
       CTR=0
     END IF
     WRITE(11,604) XX(9),XX(10),XX(11),XX(17)
C
C COUNT # OPERATING PATHS (s-t)  (GOAL #1)
C
     DWN=0
     XX(13)=0.0
     DO 35 PTH=1,np
       LKS=LKPATH(PTH,0)
       STATUS=1.0
```

E-21

```
     DO 36 LNKNUM=1,LKS
      L=LKPATH(PTH,LNKNUM)
      STS=GETARY(L,1)
      STATUS=STATUS*STS
      IF(STATUS.EQ.0.0) THEN
        DWN=DWN+1
        GO TO 35
      END IF
 36   CONTINUE
      XX(13)=XX(13)+1
 35   CONTINUE
C
C CALC RELIABILITY AS REL = # PATHS UP / TOTAL PATHS  (GOAL #1)
C
      REL=XX(13)/np
      WRITE(17,607) REL
      XX(14)=np-XX(13)
C
C COLLECT TOTAL PATHS UP FOR HRLY P CALC
C
      HUPATH=HUPATH+XX(13)
      RETURN
**************************************************
* HOURLY CHECKS
**************************************************
 4    CONTINUE
      CT=CT+1
      IF (CT.EQ.24) THEN
        DA=DA+1
        WRITE(3,605) 'DAY = ',DA
*       WRITE(6,605) 'DAY = ',DA
        CT=0
      END IF
      HOUR=HOUR+1
C
C CALC HOURLY AVAILABILITY = LINK UP TIME/TOTAL TIME - FOR EACH LINK (GOAL #3)
C
      DO 40 L=1,LINKS
       LNKDWN=GETARY(L,4)
       LNKUP=3600-LNKDWN
       AVAIL=LNKUP/3600
       CALL PUTARY(L,6,AVAIL)
C
C SAVE LINK UP TIME FOR DAILY CALC
C
       DLYUP=GETARY(L,8)
       DLYUP=DLYUP+LNKUP
       CALL PUTARY(L,8,DLYUP)
```

```fortran
C
C SAVE LINK DOWN TIME FOR DAILY CALC
C
      DLYDWN=GETARY(L,13)
      DLYDWN=DLYDWN+LNKDWN
      CALL PUTARY(L,13,DLYDWN)
C
C CALC HOURLY AVAILABILITY AS P = TOTAL CONFORM/TOTAL STATES - EACH LINK
(G#3)
C
      LKUP=GETARY(L,5)
      AVBL=LKUP/12
      CALL PUTARY(L,7,AVBL)
C
C SAVE LINK "UP"s FOR DAILY CALC
C
      DYUP=GETARY(L,9)
      DYUP=DYUP+LKUP
      CALL PUTARY(L,9,DYUP)
C
C WRITE HOURLY CALCS TO FILE
C
      NFAIL=GETARY(L,3)
      FAIL=FAIL+NFAIL
      CALL PUTARY(L,12,FAIL)
      WRITE(3,603) HOUR,L,NFAIL,LKUP,LNKUP,LNKDWN,AVBL,AVAIL
C
C CLEAR EACH LINK'S TOTAL FAILURES HOURLY
C
      CALL PUTARY(L,3,0.0)
C
C CLEAR EACH LINK'S DOWN TIME HOURLY
C
      CALL PUTARY(L,4,0.0)
C
C CLEAR EACH LINK'S UP TALLY HOURLY
C
      CALL PUTARY(L,5,0.0)
 40   CONTINUE
      IF (HOUR.EQ.24) HOUR=0
      RETURN
```

```
**************************************************
* DAILY CALCULATIONS
**************************************************
 5   CONTINUE
     DY=DY+1
C
C CALC DAILY AVAILABILITY = LINK UP TIME/TOTAL TIME - FOR EACH LINK (GOAL #3)
C
     DO 50 L=1,LINKS
      DLYUP=GETARY(L,8)
      AVTIM=DLYUP/86400
      CALL PUTARY(L,10,AVTIM)
C
C CALC DAILY AVAILABILITY AS P = TOTAL CONFORM/TOTAL STATES - EACH LINK (G#3)
C
      LKUP=GETARY(L,9)
      AVCONF=LKUP/288
      CALL PUTARY(L,11,AVCONF)
C
C WRITE DAILY CALCS TO FILE
C
      NFAIL=GETARY(L,12)
      DLYDWN=GETARY(L,13)
      WRITE(5,608) DY,L,NFAIL,LKUP,DLYUP,DLYDWN,AVTIM,AVCONF
C
C CLEAR EACH LINK'S DOWN TIME DAILY
C
      CALL PUTARY(L,13,0.0)
C
C CLEAR EACH LINK'S UP TIME DAILY
C
      CALL PUTARY(L,8,0.0)
C
C CLEAR EACH LINK'S "UP" TALLY DAILY
C
      CALL PUTARY(L,9,0.0)
 50   CONTINUE
C
 600  FORMAT(/1X,A/)
 601  FORMAT(1X,I4,3X,F6.4)
 602  FORMAT(1X,A,I4,4X,A,F6.4)
 603  FORMAT(1X,I2,2X,I4,2X,F10.1,3X,F6.1,6X,F8.1,3X,F8.1,4X,F6.4,4X,F6.
     c4)
 604  FORMAT(1X,F6.1,3X,F6.1,3X,F6.4,18X,F6.4)
 605  FORMAT(/1X,A,I4/)
 606  FORMAT(1X,I4,1X,F8.1)
 607  FORMAT(1X,F8.1)
 608  FORMAT(1X,I4,2X,I4,2X,F10.1,3X,F6.1,6X,F8.1,3X,F8.1,4X,F6.4,5X,F6.
     c4)
      RETURN
```

```fortran
      SUBROUTINE OTPUT
$INCLUDE: 'PARAM.INC'
$INCLUDE: 'SCOM1.COM'
      integer HOUR,CNT,CTR,D,DY,DA,CT,L,WARN,LINKS
      real BTWF,DLYUP,LNKDWN,NUMFL,LKUP,DYUP,FAIL,DLYDWN,FAILS
      common/ONE/NUMFL,LKUP,DYUP,BTWF,DLYUP,LNKDWN,FAIL,HOUR,CNT,CTR
     c,D,DY,DA,CT,DLYDWN,WARN,LINKS
C
C WRITE NUMBER OF FAILURES PER LINK TO FILE
C
      WRITE(8,104) 'TOTAL WARNINGS = ',WARN
      WRITE(8,103) 'TOTAL LINK FAILURES = ',XX(1)
      WRITE(8,100) 'LINK   FAILURES'
      DO 10 L=1,LINKS
       FAILS=GETARY(L,18)
       WRITE(8,102) L,FAILS
 10   CONTINUE
100   FORMAT(/1X,A/)
101   FORMAT(1X,F6.1)
102   FORMAT(1X,I4,F10.1)
103   FORMAT(/1X,A,F12.1/)
104   FORMAT(/1X,A,I6/)
      RETURN
      END
```

Path Enumeration Output - Case Study Network

Depth First Path Enumeration -- By Link Number

There are 5 links in path number   1
     60 6 9 15 77

There are 5 links in path number   2
     60 6 9 14 76

There are 7 links in path number   3
     60 6 9 13 25 54 75

There are 7 links in path number   4
     60 6 9 13 24 53 74

There are 7 links in path number   5
     60 6 9 13 23 52 73

There are 7 links in path number   6
     60 6 9 13 22 51 77

There are 7 links in path number   7
     60 6 9 13 21 50 76

There are 7 links in path number   8
     60 6 9 13 20 49 72

There are 7 links in path number   9
     60 6 9 13 20 48 71

There are 7 links in path number 10
     60 6 9 13 20 47 68

There are 7 links in path number 11
     60 6 9 13 19 46 74

There are 7 links in path number 12
     60 6 9 13 19 45 71

There are 7 links in path number 13
     60 6 9 13 19 44 70

There are 7 links in path number 14
     60 6 9 13 19 43 69

There are 7 links in path number 15
     60 6 9 13 19 42 68

There are 7 links in path number 16
60 6 9 13 18 41 70

There are 7 links in path number 17
60 6 9 13 18 40 69

There are 7 links in path number 18
60 6 9 13 17 39 67

There are 7 links in path number 19
60 6 9 13 17 38 66

There are 7 links in path number 20
60 6 9 13 17 37 65

There are 7 links in path number 21
60 6 9 13 17 36 64

There are 7 links in path number 22
60 6 9 13 17 35 63

There are 7 links in path number 23
60 6 9 13 17 34 62

There are 7 links in path number 24
60 6 9 13 17 33 61

There are 7 links in path number 25
60 6 9 13 16 32 67

There are 7 links in path number 26
60 6 9 13 16 31 66

There are 7 links in path number 27
60 6 9 13 16 30 65

There are 7 links in path number 28
60 6 9 13 16 29 64

There are 7 links in path number 29
60 6 9 13 16 28 63

There are 7 links in path number 30
60 6 9 13 16 27 62

There are 7 links in path number 31
60 6 9 13 16 26 61

There are 5 links in path number 32
        60 6 9 12 62

There are 5 links in path number 33
        60 6 9 11 61

There are 5 links in path number 34
        59 5 8 15 77

There are 5 links in path number 35
        59 5 8 14 76

There are 7 links in path number 36
        59 5 8 13 25 54 75

There are 7 links in path number 37
        59 5 8 13 24 53 74

There are 7 links in path number 38
        59 5 8 13 23 52 73

There are 7 links in path number 39
        59 5 8 13 22 51 77

There are 7 links in path number 40
        59 5 8 13 21 50 76

There are 7 links in path number 41
        59 5 8 13 20 49 72

There are 7 links in path number 42
        59 5 8 13 20 48 71

There are 7 links in path number 43
        59 5 8 13 20 47 68

There are 7 links in path number 44
        59 5 8 13 19 46 74

There are 7 links in path number 45
        59 5 8 13 19 45 71

There are 7 links in path number 46
        59 5 8 13 19 44 70

There are 7 links in path number 47
        59 5 8 13 19 43 69

There are 7 links in path number 48
        59 5 8 13 19 42 68

There are 7 links in path number 49
    59 5 8 13 18 41 70

There are 7 links in path number 50
    59 5 8 13 18 40 69

There are 7 links in path number 51
    59 5 8 13 17 39 67

There are 7 links in path number 52
    59 5 8 13 17 38 66

There are 7 links in path number 53
    59 5 8 13 17 37 65

There are 7 links in path number 54
    59 5 8 13 17 36 64

There are 7 links in path number 55
    59 5 8 13 17 35 63

There are 7 links in path number 56
    59 5 8 13 17 34 62

There are 7 links in path number 57
    59 5 8 13 17 33 61

There are 7 links in path number 58
    59 5 8 13 16 32 67

There are 7 links in path number 59
    59 5 8 13 16 31 66

There are 7 links in path number 60
    59 5 8 13 16 30 65

There are 7 links in path number 61
    59 5 8 13 16 29 64

There are 7 links in path number 62
    59 5 8 13 16 28 63

There are 7 links in path number 63
    59 5 8 13 16 27 62

There are 7 links in path number 64
    59 5 8 13 16 26 61

There are 5 links in path number 65
    59 5 8 12 62

There are 5 links in path number 66
   59 5 8 11 61

There are 4 links in path number 67
   58 4 15 77

There are 4 links in path number 68
   58 4 14 76

There are 6 links in path number 69
   58 4 13 25 54 75

There are 6 links in path number 70
   58 4 13 24 53 74

There are 6 links in path number 71
   58 4 13 23 52 73

There are 6 links in path number 72
   58 4 13 22 51 77

There are 6 links in path number 73
   58 4 13 21 50 76

There are 6 links in path number 74
   58 4 13 20 49 72

There are 6 links in path number 75
   58 4 13 20 48 71

There are 6 links in path number 76
   58 4 13 20 47 68

There are 6 links in path number 77
   58 4 13 19 46 74

There are 6 links in path number 78
   58 4 13 19 45 71

There are 6 links in path number 79
   58 4 13 19 44 70

There are 6 links in path number 80
   58 4 13 19 43 69

There are 6 links in path number 81
   58 4 13 19 42 68

There are 6 links in path number 82
   58 4 13 18 41 70

There are 6 links in path number 83
        58 4 13 18 40 69

There are 6 links in path number 84
        58 4 13 17 39 67

There are 6 links in path number 85
        58 4 13 17 38 66

There are 6 links in path number 86
        58 4 13 17 37 65

There are 6 links in path number 87
        58 4 13 17 36 64

There are 6 links in path number 88
        58 4 13 17 35 63

There are 6 links in path number 89
        58 4 13 17 34 62

There are 6 links in path number 90
        58 4 13 17 33 61

There are 6 links in path number 91
        58 4 13 16 32 67

There are 6 links in path number 92
        58 4 13 16 31 66

There are 6 links in path number 93
        58 4 13 16 30 65

There are 6 links in path number 94
        58 4 13 16 29 64

There are 6 links in path number 95
        58 4 13 16 28 63

There are 6 links in path number 96
        58 4 13 16 27 62

There are 6 links in path number 97
        58 4 13 16 26 61

There are 4 links in path number 98
        58 4 12 62

There are 4 links in path number 99
        58 4 11 61

There are 6 links in path number 100
        57 3 7 10 15 77

There are 6 links in path number 101
        57 3 7 10 14 76

There are 8 links in path number 102
        57 3 7 10 13 25 54 75

There are 8 links in path number 103
        57 3 7 10 13 24 53 74

There are 8 links in path number 104
        57 3 7 10 13 23 52 73

There are 8 links in path number 105
        57 3 7 10 13 22 51 77

There are 8 links in path number 106
        57 3 7 10 13 21 50 76

There are 8 links in path number 107
        57 3 7 10 13 20 49 72

There are 8 links in path number 108
        57 3 7 10 13 20 48 71

There are 8 links in path number 109
        57 3 7 10 13 20 47 68

There are 8 links in path number 110
        57 3 7 10 13 19 46 74

There are 8 links in path number 111
        57 3 7 10 13 19 45 71

There are 8 links in path number 112
        57 3 7 10 13 19 44 70

There are 8 links in path number 113
        57 3 7 10 13 19 43 69

There are 8 links in path number 114
        57 3 7 10 13 19 42 68

There are 8 links in path number 115
        57 3 7 10 13 18 41 70

There are 8 links in path number 116
        57 3 7 10 13 18 40 69

There are 8 links in path number 117
    57 3 7 10 13 17 39 67

There are 8 links in path number 118
    57 3 7 10 13 17 38 66

There are 8 links in path number 119
    57 3 7 10 13 17 37 65

There are 8 links in path number 120
    57 3 7 10 13 17 36 64

There are 8 links in path number 121
    57 3 7 10 13 17 35 63

There are 8 links in path number 122
    57 3 7 10 13 17 34 62

There are 8 links in path number 123
    57 3 7 10 13 17 33 61

There are 8 links in path number 124
    57 3 7 10 13 16 32 67

There are 8 links in path number 125
    57 3 7 10 13 16 31 66

There are 8 links in path number 126
    57 3 7 10 13 16 30 65

There are 8 links in path number 127
    57 3 7 10 13 16 29 64

There are 8 links in path number 128
    57 3 7 10 13 16 28 63

There are 8 links in path number 129
    57 3 7 10 13 16 27 62

There are 8 links in path number 130
    57 3 7 10 13 16 26 61

There are 6 links in path number 131
    57 3 7 10 12 62

There are 6 links in path number 132
    57 3 7 10 11 61

There are 4 links in path number 133
    56 2 15 77

There are 4 links in path number 134
      56 2 14 76

There are 6 links in path number 135
      56 2 13 25 54 75

There are 6 links in path number 136
      56 2 13 24 53 74

There are 6 links in path number 137
      56 2 13 23 52 73

There are 6 links in path number 138
      56 2 13 22 51 77

There are 6 links in path number 139
      56 2 13 21 50 76

There are 6 links in path number 140
      56 2 13 20 49 72

There are 6 links in path number 141
      56 2 13 20 48 71

There are 6 links in path number 142
      56 2 13 20 47 68

There are 6 links in path number 143
      56 2 13 19 46 74

There are 6 links in path number 144
      56 2 13 19 45 71

There are 6 links in path number 145
      56 2 13 19 44 70

There are 6 links in path number 146
      56 2 13 19 43 69

There are 6 links in path number 147
      56 2 13 19 42 68

There are 6 links in path number 148
      56 2 13 18 41 70

There are 6 links in path number 149
      56 2 13 18 40 69

There are 6 links in path number 150
      56 2 13 17 39 67

There are 6 links in path number 151
      56 2 13 17 38 66

There are 6 links in path number 152
      56 2 13 17 37 65

There are 6 links in path number 153
      56 2 13 17 36 64

There are 6 links in path number 154
      56 2 13 17 35 63

There are 6 links in path number 155
      56 2 13 17 34 62

There are 6 links in path number 156
      56 2 13 17 33 61

There are 6 links in path number 157
      56 2 13 16 32 67

There are 6 links in path number 158
      56 2 13 16 31 66

There are 6 links in path number 159
      56 2 13 16 30 65

There are 6 links in path number 160
      56 2 13 16 29 64

There are 6 links in path number 161
      56 2 13 16 28 63

There are 6 links in path number 162
      56 2 13 16 27 62

There are 6 links in path number 163
      56 2 13 16 26 61

There are 4 links in path number 164
      56 2 12 62

There are 4 links in path number 165
      56 2 11 61

There are 4 links in path number 166
      55 1 15 77

There are 4 links in path number 167
      55 1 14 76

There are 6 links in path number 168
        55 1 13 25 54 75

There are 6 links in path number 169
        55 1 13 24 53 74

There are 6 links in path number 170
        55 1 13 23 52 73

There are 6 links in path number 171
        55 1 13 22 51 77

There are 6 links in path number 172
        55 1 13 21 50 76

There are 6 links in path number 173
        55 1 13 20 49 72

There are 6 links in path number 174
        55 1 13 20 48 71

There are 6 links in path number 175
        55 1 13 20 47 68

There are 6 links in path number 176
        55 1 13 19 46 74

There are 6 links in path number 177
        55 1 13 19 45 71

There are 6 links in path number 178
        55 1 13 19 44 70

There are 6 links in path number 179
        55 1 13 19 43 69

There are 6 links in path number 180
        55 1 13 19 42 68

There are 6 links in path number 181
        55 1 13 18 41 70

There are 6 links in path number 182
        55 1 13 18 40 69

There are 6 links in path number 183
        55 1 13 17 39 67

There are 6 links in path number 184
        55 1 13 17 38 66

There are 6 links in path number 185
    55 1 13 17 37 65

There are 6 links in path number 186
    55 1 13 17 36 64

There are 6 links in path number 187
    55 1 13 17 35 63

There are 6 links in path number 188
    55 1 13 17 34 62

There are 6 links in path number 189
    55 1 13 17 33 61

There are 6 links in path number 190
    55 1 13 16 32 67

There are 6 links in path number 191
    55 1 13 16 31 66

There are 6 links in path number 192
    55 1 13 16 30 65

There are 6 links in path number 193
    55 1 13 16 29 64

There are 6 links in path number 194
    55 1 13 16 28 63

There are 6 links in path number 195
    55 1 13 16 27 62

There are 6 links in path number 196
    55 1 13 16 26 61

There are 4 links in path number 197
    55 1 12 62

There are 4 links in path number 198
    55 1 11 61

APPENDIX G: How to Use The EXCEL Control Charting Spreadsheets

There are two spreadsheets for each type of control chart. The first one computes the control limits and the second constructs the control chart. Spreadsheets were written for four types of control charts: **p chart, np chart, XmR chart, and x-bar and R chart**. The use of each is discussed below. Upon opening any of the spreadsheets, it is wise to immediately use the **'Save as'** command to save it to a working filename. This will help with the prevention of corrupting the original files. The chart spreadsheets are designed to hold up to 720 data points, hence the storage size of a spreadsheet can be large when full. It is recommended that a *minimum* of 8 MB of RAM are available, especially if more than one spreadsheet is open at a time. Save data often in case your RAM limitations are exceeded.

p Chart

p Control Limits (plim.xls)

The control limits can be computed by either estimating standards from inputted sample data, or by simply inputting the theoretical standards if they are known. If the theoretical standards are known, input them into the *second* cell under the headings **'pbar'** (mean) and **'std dev'** (standard deviation). Notice this row is labeled **'Theoretical'** to the far right. The control limits will appear under their appropriate column headings of **'LCL', 'CL',** and **'UCL'**; the Lower Control Limit, Center Line, and Upper Control Limit respectively. Also, under the headings below the control limits will appear the 1-sigma and 2-sigma lower and upper warning limits for optional usage on the control charts. A sample 'plim.xls' spreadsheet is shown next for reference:

PerfMeas	SampleNum	p Value	Out-of-Control?	pbar	calc	LCL(p)	CL(p)	UCL(p)	
Rel p up	1	0.987		0.9420132	0.0266347	0.8621091	0.9420132	1	Estimated
	2	0.961		0.9421	0.0266	0.8623	0.9421	1	Theoretical
Smpl Size	3	0.961							
77	4	0.961							
	5	0.9221							
	6	0.9481		L_1SIGMA	U_1SIGMA	L_2SIGMA	U_2SIGMA		
	7	0.9351		0.9153785	0.9686479	0.8887438	0.9952826	Estimated	
	8	0.9221		0.9155	0.9687	0.8889	0.9953	Theoretical	
	9	0.9481							
	10	0.9481							
	11	0.974							
	12	0.9481							
	13	0.9091							
	14	0.8961							
	15	0.9351							

Sample 'plim.xls' Spreadsheet for p Chart Control Limits

If the standards need to be estimated, the sample data on the desired p value should be inputted under the column heading 'p Value'. A column is provided to enter the sample number if desired. The sample size used to compute the sample p values must be inputted under the heading 'Smpl Size' to the far left. Also located here at the very top left of the spreadsheet is a cell to place the name of the performance measure being used if desired. Once again, the control limits will appear under their appropriate headings in the first row labeled 'Estimated' on the far right. The estimated 1-sigma and 2-sigma lower and upper warning limits will also appear under their appropriate headings in the row labeled 'Estimated.' Additionally, there is a column with the heading 'Out-of-Control?' in the middle of the spreadsheet. The formula contained in the first cell under this heading can be copied and pasted down this column for each of the entered p values. This will indicate if any of the sample p values are out-of-control with respect to the estimated control limits. Any indicated out-of-control p values can then be investigated for exclusion from the control limits computations. (see Section 3.1.5 Trial Control Limits)

p Control Chart (p.xls)

Upon opening 'p.xls' EXCEL will ask ' This document contains links. Reestablish links?' Answer **No**. When the blue interface screen appears, save the file as a working file. On the interface screen, there are three buttons for: (1) Select a Performance Measure (or inserting a new one), (2), Edit the Control (and Warning) Limits and (3) Delete a Performance Measure. For starting a new file, either (1) or (2) above can be accomplished first.

For (2), **Edit the Control (and Warning) Limits**, simply press the button and enter the control and warning limits as previously calculated using 'plim.xls' in their appropriate box. The control and warning limits entered here will affect the charts of all performance measures in the entire spreadsheet. However they can be edited at any time. Warning limits are optional since zeroes entered in the upper 1sigma and/or upper 2-sigma limits boxes, results in no plotting of the respective warning limits.

For (1), **Select a Performance Measure**, again press the button and enter a new performance measure or select from a drop-down list of existing ones (the name NewMeas has no data associated with it). After pressing **OK**, EXCEL will ask, 'Selection too big, Continue without undo?' Answer **YES**. A spreadsheet will appear identified by the performance measure name entered. Data can now be entered one point at a time using the gray button labeled **'Enter Data'** to the right, or it can be pasted in from another existing spreadsheet. To paste in a block of data, the performance measure sheet must be unprotected. Use the **'Tools, Protection, Unprotect Sheet'** command from the pull-down menus to accomplish this. The p values can be pasted into the column labeled **'p value.'** The column labeled **'Smpl Number'** *must* be filled for each p value in this spreadsheet (as opposed to its optional status in 'plim.xls'). This can quickly be accomplished using the **'Edit, Fill, Series'** command from the pull-down menus. Next, the box labeled **'Total Samples Available'** must be entered and the **'Last'**

point desired to be plotted must also be entered (be sure to either press the enter key or click on another cell in the worksheet after entering the 'Last' point or the 'Plot' button will not work. Now select the **'Plot'** button. The chart is automatically plotted. Once this is complete, there may be a diagonal line of points on the chart. To remedy this, select the chart by clicking it once, and then select the **'Chart Wizard'** button on the toolbar. A box will appear for **'Chart Wizard - Step 1 of 2,'** select the **'Next'** button. Another box will appear for **'Chart Wizard - Step 2 of 2,'** in the box labeled 'Use First (0) Columns for X Data' make sure there is a '1', and in the box labeled 'Use First (0) Rows for Legend Text' make sure there is also a '1'. This should clear up any errors in the appearance of the chart. The chart is now finished. The blue interface screen can be selected again for editing the control limits or entering/selecting other performance measures as desired. There is a pull-down menu labeled **'Control Charts'** at the top of the screen for returning to the interface screen. Any editing of the control or warning limits is shown immediately on the currently plotted chart. If more data point are added to a performance measure, make sure the 'Total Samples Available' and 'Last' point boxes are correctly altered and then select the 'Plot' button. The spreadsheet is equipped to handle up to 720 data points as currently written.

For (3), **Delete a Performance Measure,** press the button and select the desired performance measure from a drop-down list of existing ones and select **OK**.

np Chart

np Control Limits (nplim.xls)

The 'nplim.xls' spreadsheet is operated the same as 'plim.xls' above except that np values must be entered instead of p values.

np Control Chart (np.xls)

The 'np.xls' spreadsheet is operated the same as 'p.xls' above except that np values must be entered instead of p values.

XmR Charts

XmR Control Limits (xmrlim.xls)

The 'xmrlim.xls' spreadsheet is operated the same as 'plim.xls' above with the following exceptions:

For theoretical limits calculation, the known standards must be inputted into the *second* cell under the headings '**Xbar**' (mean) and '**mRbar**' (standard deviation). Note that the *standard deviation* (*not* the theoretical mRbar) must be inputted into the second cell under mRbar. Notice again this row is labeled 'Theoretical' to the far right. The control limits will appear under their appropriate column headings of 'LCL', 'CL', and 'UCL' for both the X and mR charts as will the appropriate warning limits. See the sample 'xmrlim.xls' spreadsheet below for reference.

PerfMeas	SampleNum	Value	mRange	Out-of-Control?	Xbar	mRbar	LCL(X)	CL(X)	UCL(X)	CL(mR)	UCL(mR)	
DwnLinks	1	1			4.4652778	1.3344948	0.91608955	4.465277778	8.014466005	1.334494774	4.359794425	Estimated
	2	3	2		4.46	2.0494	0	4.46	10.6082	2.3117232	7.5540884	Theoretical
	3	3	0		n =	2						
	4	3	0		D1=	0						
	5	6	3		D2=	3.686	L_1SIGMA(X)	U_1SIGMA(X)	L_2SIGMA(X)	U_2SIGMA(X)		
	6	4	2		D3=	0	3.282215035	5.64834052	2.099152293	6.831403263	Estimated	
	7	5	1		D4=	3.267	2.4106	6.5094	0.3612	8.5588	Theoretical	
	8	6	1		d2=	1.128	L_1SIGMA(mR)	U_1SIGMA(mR)	L_2SIGMA(mR)	U_2SIGMA(mR)		
	9	4	2		d3=	0.853	0.325342254	1	0	1	Estimated	
	10	4	0				0.563585	4.0598814	0	5.8079996	Theoretical	
	11	2	2									
	12	4	2									
	13	7	3									
	14	8	1									
	15	5	3									

Sample 'xmrlim.xls' Spreadsheet for XmR Chart Control Limits

For **estimating** control limits from sample data, the individual values must be inputted in the column labeled '**Value**,' the SampleNum column is optional, and now in addition to copying and pasting the **Out-of-Control?** formula down its column, the '**mRange**' formula located in the *second* cell underneath its heading must also be copied and pasted for each sample value underneath

XmR Control Charts (xmr.xls)

The 'xmr.xls' spreadsheet is operated the same as 'p.xls' above except that individual values must be entered instead of p values, and there is a separate button on the blue interface screen for entering the warning limits.

x-bar and R Charts

x-bar and R Control Limits (xbrlim.xls)

The 'xbrlim.xls' spreadsheet is operated the same as 'xmlim.xls' above with the following exceptions:

For theoretical limits calculation, the known standards must be inputted into the *second* cell under the headings '**Xbar_bar**' (mean) and '**Rbar**' (standard deviation). Note again that the *standard deviation* (*not* the theoretical Rbar) must be inputted into the second cell under Rbar. Notice again this row is labeled '**Theoretical**' to the far right. This spreadsheet is set up for a sample size of 24. If a different sample size is desired, the desired sample size must be entered into the cell below the label '**Sample Size**' on the far left and the corresponding **tabulated constants** for that sample size must be entered in their respective cells under the 'Rbar' column. The control limits and warning limits will appear under their appropriate column headings for both the x-bar and R charts. See the

sample 'xbrlim.xls' spreadsheet below for reference.

PerfMeas	SampleNum	Value	Smpl Max	Smpl Min	Xbar	Range	SmplNum	SmplXbar	SmplRange	Out-of-Control?
DnLk 1hr d	1	4	9	0	4	9	1	4	9	
	1	3					2	4.875	8	
Sample	1	5					3	5	9	
Size	1	7					4	3.833333	8	
24	1	5					5	3.958333	10	
	1	2					6	4.5	6	
	1	4					7	4.958333	6	
	1	8					8	4.916667	7	
	1	3					9	4.333333	8	
	1	2					10	5.75	7	Xbar
	1	3					11	4.916667	8	
	1	7					12	4.458333	8	
	1	6					13	3.708333	5	
	1	1					14	4.125	7	
	1	4					15	4.541667	6	
	1	9					16	4.5	7	
	1	5					17	4.541667	11	
	1	2					18	4.5	11	
	1	5					19	4.416667	7	
	1	2					20	4.25	8	
	1	3					21	3.166667	8	Xbar
	1	0					22	4.75	10	
	1	4					23	4	7	
	1	2					24	4.083333	7	
	2	6	9	1	4.875	8	25	4.5	9	
	2	4					26	4.5	6	
	2	4					27	3.791667	4	
	2	4					28	4.208333	9	
	2	4					29	5.291667	12	
	2	3					30	4.041667	6	

Xbar_bar	Rbar	LCL(X)	CL(X)	UCL(X)	LCL(R)	CL(R)	UCL(R)			
4.4138889	7.8	3.187571818	4.413888889	5.640205962	3.5178	7.8	12.0744	Estimated		
4.46	2.0494	3.20500393	4.46	5.71499607	3.6048946	7.982413	12.3599314	Theoretical		
n =	24									
D1=	1.759									
D2=	6.031	L_1SIGMA(X)	U_1SIGMA(X)	L_2SIGMA(X)	U_2SIGMA(X)	L_1SIGMA(R)	U_1SIGMA(R)	L_2SIGMA(R)	U_2SIGMA(R)	
D3=	0.451	4.005116531	4.822661246	3.596344174	5.231433604	6.374172015	9.225827985	4.948344031	10.85165597	Estimated
D4=	1.548	4.041667977	4.878332023	3.623335954	5.296664046	6.5232402	9.4415858	5.0640674	10.9007586	Theoretical
d2=	3.895									
d3=	0.712									

Sample 'xbrlim.xls' Spreadsheet for x-bar and R Chart Control Limits

For estimating control limits from sample data, the *individual values* must be inputted in the column labeled '**Value**,' and the SampleNum column is again optional. The desired sample size must now be inputted into the cell below the label '**Sample Size**' and in addition, some formula copying must be accomplished. This formula copying will be explained using the default value of sample size 24. The entire block of cells under the headings '**Smpl Max**', '**Smpl Min**', '**Xbar**', and '**Range**' from the first cell under the headings to the last cell of the sample (i.e. the first to the 24th cell under the headings - note that this includes mostly empty cells) must be copied and then pasted down the column directly below for all of the sample data. This is a hashed area on the sample spreadsheet. After pasting, select the entire area under the *two* headings, '**Xbar**' and '**Range**'. From the pull-down menus select '**Edit, Go To, Special, Formulas, OK**.' The cells containing the sample means and ranges will now be selected. Select copy and then paste these values under the headings, '**SmplXbar**' and '**SmplRange**.' Copy and paste the **Out-of-Control?** formula down its column as described earlier. The control and warning limits will appear under their appropriate column headings for both the x-bar (X) and R charts in the row labeled '**Theoretical**.'

x-bar and R Control Charts (xbr.xls)

The 'xbr.xls' spreadsheet is operated the same as 'xmr.xls' above except that *sample* values must be entered instead of individual values.

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VITA

Captain Maureen E. Borgia was born on 10 November 1966 in Ephrata, Pennsylvania. She graduated from Warwick High School in Lititz, Pennsylvania in June 1985 and accepted an appointment to attend the U.S. Air Force Academy where she graduated with a Bachelor of Science Degree in Engineering Physics in May 1989. Upon receiving a regular commission in the U.S. Air Force, Captain Borgia entered Specialized Undergraduate Navigator Training at Mather AFB, CA where she earned Distinguished Graduate in May 1990. After earning Distinguished Graduate upon completion of KC-135 Combat Crew Training at Castle AFB , CA, her first operational tour was at Grissom AFB, IN.

From February 1991 to May 1991, Captain Borgia participated in Operations Desert Storm and Desert Calm logging over 40 combat hours and earning the Air Medal and the Aerial Achievement Medal for her accomplishments. During her tour at Grissom AFB, Captain Borgia was qualified as one of the few KC-135 Receiver Navigators in the U.S. Air Force and earned her Instructor Navigator status with only 725 hours of the 700 required.

In August 1993, Captain Borgia entered the Graduate School of Engineering at the Air Force Institute of Technology where she earned her Master of Science Degree in Operations Research. Upon graduation in June 1995, Captain Borgia was assigned to the 33 FLTS, McGuire AFB, NJ.

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This study investigates the application of statistical process control methods to monitoring the performance of a communication network. The methods applied include four different types of control charts. The literature search uncovered only one previous study that used a control chart to monitor a communication network.

Using a case study of a communication network, four important issues for proper control chart usage are emphasized. These issues are: proper data collection rate due to autocorrelation, proper subgrouping of the data, ensuring that count data conforms to the assumptions of the binomial probability model before implementing p or np control charts, and viability of using subgroups of attribute data as measurement data on an x-bar chart. The results indicate that control charts are indeed a viable method for monitoring a communication network's performance over time, especially when the available data on the network is limited.

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